Design and Outcomes of Computer-Based Cognitive Prosthetics for Brain Injury: A Field Study of Three Subjects

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Three traumatic brain injury (TBI) patients achieved a significant increase in level of function in a short period of time using a Computer-Based Cognitive Prosthesis (CBCP). A CBCP is a compensatory strategy which applies computer science concepts to brain injury rehabilitation. One-of-a-kind software is designed to assist the brain injury survivor in performing functional activities. New techniques of rehabilitation are also applied. Research subjects were between one and five years post injury. Patients were able to make substantial contributions to the design of their prosthetic software. Increases in level of functioning were seen both in everyday activities targeted for the intervention, as well as generalized increase on neurobehavioral and psychological dimensions.

Keywords: Cognitive prosthesis; cognitive rehabilitation; participatory design; computer science; human computer interaction; computers in rehabilitation

Enduring cognitive deficits from TBI interfere with people's ability to return to premorbid functioning, and have been remarkably resistant to remediation.[1-3] While computers are now widely used in cognitive rehabilitation,[4] the rehabilitation literature on the prosthetic use of computers is minimal.[5] Kirsch et al.[6] introduced the term "cognitive orthosis" to the rehabilitation literature, as a task guidance system, to assist brain injury patients in performing a well-structured task. Their empirical work involved several subjects with a different task for each subject, and overall success in having the patient perform the target task in a research hospital milieux. Henry et al.[7] reported the design of specialized hardware, including speech output, to help guide cognitively impaired patients through diverse tasks. Parente et al.[8-10] have described several cases in which expert system software was used to customize complex software to assist brain injury patients in the performance of their work tasks. Chute et al.[11] describe the concept of computer-based software called "Prosthesisware," which can be used for both physical and cognitive disabilities. Egert[12] discussed the importance of computer interface design to create usable software for brain injury patients. In the area of language disorders, there is substantial literature on augmentive and

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alternative communication that uses computer technology to overcome dysarthria coupled with neuromotor deficits,[13] as well as expressive aphasias.[14,15] Cole and colleagues, writing in the computer science and engineering fields,[16–20] have reported a few case studies involving prosthetic software. They were able to demonstrate that a prosthetic software system could be designed and used by a patient at home for unstructured, as well as structured activities.

APPLYING COMPUTER SCIENCE CONCEPTS TO COGNITIVE REHABILITATION

Several areas of computer science have goals and models which are similar to those of cognitive rehabilitation. It is important to note that these computer science models incorporate non-computer tasks and activities, so that an analysis can take a broader perspective than just hardware and software.

Office Information Systems

Office information systems (OIS) are used to solve practical problems of individuals. OIS goals generally involve increasing the cognitive productivity of the individual, enabling them to increase their cognitive productivity (i.e., increasing their level of function on cognitive tasks with the assistance of appropriate technology[21]). Analysis of needs focuses on the kinds of activities the individual performs, and identifies those activities where there is a specific need for productivity improvement. Activities are defined in terms of work subtasks. The goal of the information system is to improve productivity for the activity as a whole. The model of increasing cognitive productivity is very appropriate to cognitive rehabilitation, and represents a functional approach to rehabilitation.

Computer Human Interaction

Methods of designing "user friendliness" into a system's performance are the concern of the computer science area of computer human interaction.[22] However, there are two important misconceptions about user friendliness that have particular relevance to cognitive rehabilitation. The first misconception is that user friendliness is a single measure and is a characteristic of a device. There are in fact many different criteria that the specialist applies when evaluating the usability of a system design (see Figure 1). Perhaps the most relevant to cognitive rehabilitation are (1) work completion time, (2) training time, (3) errors, and (4) error recovery.[23] Reducing work completion time provides time to perform other activities. In the rehabilitation context, often the patient is unable to successfully perform an activity which is the object of the therapy, as in the case reports below. Then the individual moves from being unable to perform an activity, to achieving the ability to perform the activity. Training time is particularly important for brain injury because frequently, various cognitive impairments can impede the general ability to learn a compensatory strategy. For the interface designer addressing the needs of a specific individual, as opposed to a large anonymous group, it should be possible to develop a design that greatly reduces the training time. Our lab routinely achieves training time with brain injury survivors of a few minutes to under an hour.

The second misconception about user friendliness is that something is inherently user friendly

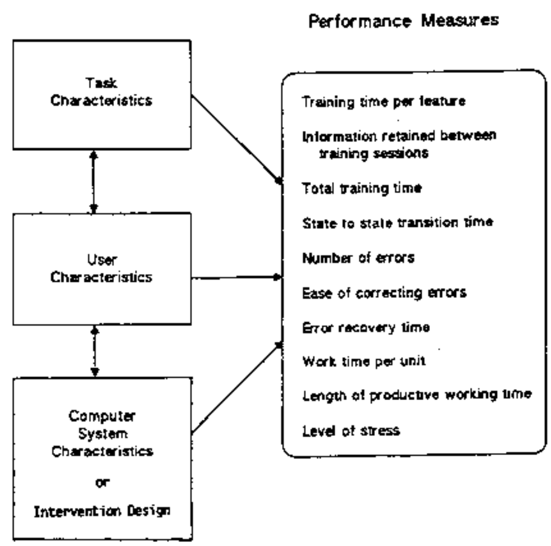

Figure 1. Computer human interaction: "User friendly" performance measures and their determinants.

or not. Figure 1 shows shows that performance ("user friendliness") depends on (1) characteristics of the user, (2) characteristics of the user's activities, and (3) design of the system or intervention. The system consists of both manual and computer-based components, and thus is analogous to a compensatory strategy. User friendliness is not a characteristic of the software, but depends on who is using it and for what activities. From this model one can see that individual differences, and task-detail differences make it highly unlikely that the same compensatory strategy (without significant modification in design details) will work equally well for different individuals, particularly when cognitive deficits are present. Furthermore, a compensatory strategy designed for an individual will not be equally effective across different tasks and activities.

Patient Participation in Design

A third concept from computer science is participatory design. This design strategy involves the user in the design of the software that will ultimately increase their productivity. Participatory design was developed to overcome problems of design inadequacy caused by inaccurate data: important details of user behavior which could not be captured by systems analysts during the data collection and analysis stage.[24] Inaccurate measurements of user behavior compromise the usability of the system. The details of the design are more important to system performance than the basic concept of the design. These details may involve situational variables that were not evaluated, or user characteristics that have not been measured, but that the user recognizes as being important to his or her ability to perform an activity when and where it is appropriate. In essence, the user can serve as a versatile and accurate measurement instrument for design parameters, and the user is often in the best position to provide information.

COMPUTER-BASED COGNITIVE PROSTHESIS MODEL

These concepts from computer science are applied to issues of cognitive rehabilitation in the CBCP model (see Figure 2). The model shows a functionally impaired TBI patient who has been unsuccessful in performing diverse activities since the injury. Each time a patient is able to perform another target activity, there is an increase in self-sufficiency. Through a unique design process, a CBCP is customized to the needs of the patient. The effectiveness of the CBCP depends on the fit between the CBCP, and both the patient's characteristics and the target activity's characteristics. Increased effectiveness can be achieved by bridging deficits that impair activity performance, or by enabling greater use of residual resources that can be used in performing the target activity.

Optimal design of the personal productivity modules is critical. If the patient can perform a subtask, then that subtask should be assigned to the patient, even if the computer is faster or more reliable. To take away a subtask the patient can perform removes an opportunity for success and for improved self-esteem. Similarly, prosthetic software needs to take on those subtasks that the patient cannot successfully perform. Testing in context is critical: a subtask that is a disability in one activity may well be an ability in the context of another activity, and vice versa. Identifying the patient's abilities-in-context and disabilities-in-context can enable the therapist to increase the effectiveness of compensatory strategies.

CBCPs have certain extra capabilities inherent in the technology. One is the collection of detailed data as the patient performs activities outside the rehab suite. This data is processed into an analysis for the therapist. A second capability is the off-site therapy session, where the patient and therapist use remote control software and a telephone voice line.

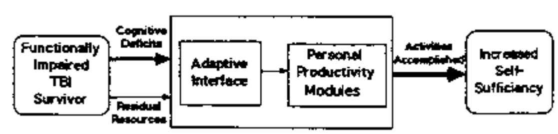

Figure 2. Computer-based cognitive prosthesis for brain injury.

METHODS

An objective of this study was to provide additional support for the proposition that a CBCP can be designed to enable TBI patients to perform an activity that has been elusive since the injury, despite efforts at cognitive remediation; the activity was to be performed in their natural environment, without the presence of therapists or caregivers. The CBCP would be customized to the needs of the individual subject, in performing an activity selected as the objective for the intervention. An additional goal was to study the process of designing successful prosthetic interventions, including the manner by which therapists provide CBCP services.

Procedures called for the selection of three patients from a rehabilitation hospital's current outpatient census. Selection criteria included: no expectation of spontaneous recovery; family and social supports; likelihood of attending sessions; the possibility that software with scheduling, or "to do list" features is appropriate for meeting unmet rehabilitation goals (without doing detailed design of the therapeutic prosthetic intervention); and failure of alternative compensatory strategies to remediate the deficit. However, it was recognized that additional software modules might be needed depending on the needs of the patient. Qualified patients were rated on this scale by their therapist. The three patients with the highest ratings were given informed consent, both orally and in writing, in accordance with procedures approved by the hospital's Institutional Review Board. All patients accepted the offer of participation.

Design

Each subject's therapist had previously identified a general rehabilitation problem that would be the focus of this CBCP study. The problem was analyzed in depth, which involved a review of rehabilitation efforts and a site visit to the patient's home. The purpose of the home visit was to collect data on activity performance, especially details of successful and unsuccessful compensatory strategies. A review was then conducted to try to understand the nature of the failures.[25,26] The detailed initial intervention goal was specified. An initial intervention design was developed jointly with computer scientists and cognitive rehabilitation therapists. Each therapist then developed on paper an interface design and a functional description of how scheduling and "to do" software should be configured to serve the needs of the patient. The systems team took this design information and developed interface and application models that could be tested and customized in sessions with each subject. Often, the therapists provided verbal instructions as the interface was being designed by the systems team. All of the subjects played a significant role in the redesign of their software. Two subjects became the primary designers of their initial system.

Testing and Redesign

The design was then presented to the subject in design and testing sessions as a series of components. Redesign is a normal and critical part of testing. Test sessions involved a number of different tasks for a subject to assess: (1) the ability to understand, without confusion, the information presented by the computer software, and (2) the ability to shift from one part of the task to another. This is similar to the error-free design approach of Wilson.[27] Test sessions were also an opportunity for the subject to select colors for all objects on the screen, request sound cues or music, as well as an opportunity to request any changes in the software. These requests typically came spontaneously as the subject was, under the protocol, using or testing the software. Each of the modules was tested, redesigned where necessary, and accepted. Subjects were trained at the rehabilitation facility on the use of the system as a whole, then the CBCP was delivered to the subject for use. Redesign continued as the subject found features to modify, add, or remove.

Computer Systems

Computer configurations were Intel-based 386–SX computers running under MS–DOS 5.0. Multi-tasking was available under DESQview operating system enhancement. Software was developed with the Clipper programming language and libraries. For two of the subjects, desktop computers were appropriate, and were placed in a central location in the patient's home that matched their pattern of activities. The third patient was provided with a "notebook" computer because its use was to be both in the home and at work. Dedicated telephone lines were provided for the subjects with desktop computers; a phone line was to have been provided for the third, but did not happen because of events unrelated to research goals.

Remote communication software was used so the therapists could have remote work sessions with the subjects. They talked over one phone line, and worked on the computer over the dedicated phone line. Both subject and therapist simultaneously saw the same information on their respective monitors and could use the software through their respective keyboards.

Research Design

The study is a single-subject study of three subjects, with each as a replicate; this allows for aggregation of some of the data. The study design is also a quasi-experiment with each subject serving as her or his own control. Outpatients diagnosed with TBI and at least one year post injury, were the study population. In addition, a functional problem became a candidate goal for the study only if conventional techniques had failed to remediate the problem.

The study design called for one intervention per subject, a two-week interval between starting with a new subject, and a total intervention period of 12 weeks, beginning in April 1992. When it became obvious that subjects were achieving the intervention goals much faster than anticipated, the design was expanded to add intervention goals.

Subject 1

Initial goal:

Facilitate punctuality; improve ability to work with the concept of time; reduce impulsive behavior to interrupt an activity; improve attention to detail

Goal 2:

Enable communication between patient and therapist via computer

Subject 2

Initial goal:

Initiate an unsupervised activity in the home with cueing at a preset time daily; if possible, to initiate an unsupervised activity spontaneously during the day

Goal 2:

Follow a brief daily schedule of activities

Goal 3:

Provide a medium of scheduled, structured writing; enhance reading activity and comprehension

Goal 4:

Increase ability to make decisions; follow increasingly complex sequence pattern

Subject 3

Initial goal:

Set priorities in her daily activities; provide memory support for activities; have a socially appropriate compensatory strategy which could be used anytime, anywhere

Goal 2:

Support ability to track and manage work by providing organization and structure

Figure 3. Initial and additional intervention goals for subjects.

RESULTS

The initial goals and additional goals for each of the three subjects are presented in Figure 3. Figure 3 shows that the backbone modules were used to resolve diverse cognitive deficits, among them initiation, prioritizing, memory, impulsivity, and facilitating punctuality.

For purposes of homogeneity, the initial intervention goal was to utilize features of scheduling or a "to do list." Because the design of CBCP is driven by the needs of the patient, there must be the capacity to produce prosthetic software with whatever features are needed by the patient. The most unusual feature requested was software to compose musical cues. A detailed list of intervention goals and software features is available.[28]

Figure 4 shows the number of weeks of prosthetic intervention required to achieve the initial rehabilitation goal. Subject 1 achieved his goal by

Subject	Weeks to Achieve Goal
Subject RJ:	2
Subject SC:	1
Subject DS:	1
	Average: 1

Figure 4. Weeks to achieve initial intervention goal.

the second week. For subjects 2 and 3, the intervention was resolved within the first week. It is significant that previous cognitive rehabilitation had been unsuccessful in resolving these functional disabilities.

CASE REPORTS

There are three case study reports. In addition, the cognitive rehabilitation therapists commented on the clinical effect of the intervention technology.

Subject 1: "RJ"

RJ sustained multiple injuries in a malicious assault in April 1986. He was unconscious for approximately four hours, had right and left parietal skull fractures, right posterior frontal lobe contusion, left frontal tip contusion, and left and right posterior frontal hematomas. A neuropsychological evaluation performed in February 1988 found bilateral cerebral impairment primarily of the frontal lobes, disinhibition, poor organization and planning, impaired judgment, inconsistent attention and concentration, and poor visual memory.

Prior to his head injury, RJ had worked as a successful commercial artist which afforded him an affluent lifestyle. He enjoyed a variety of cultural activities and an active social life. After his head injury, he was unable to live independently. His temporal processing was significantly impaired, he was plagued by serious memory problems which made it difficult for him to follow a routine, remember appointments and obligations, and take his medications on schedule. He had difficulty shifting from one activity to another during the day, and was unable to comprehend events days and weeks in the future.

RJ had been receiving cognitive therapy for three years with emphasis on structuring and following daily activity patterns, and utilizing a manual schedule as a compensatory strategy. Major problem areas included poor planning ability, impulsivity, poor attention to detail, and inconsistent compliance with daily routine. The clinician had exhausted both conventional and nonconventional therapy approaches. In addition, RJ had developed an elaborate system consisting of several sets of manual scheduling devices. The sum total of these devices was not sufficient to achieve compliance with routine activities and reduce impulsive behaviors. Moreover, these devices did not provide the structure RJ needed to be able to think in terms of the future. His calendars and journals were archival: they were records of events which had already occurred.

The goal of the first intervention was to enable him to follow a daily schedule (see Figure 3). Through a series of design sessions, a customized daily schedule was developed, and he played a significant role in the design of his CBCP.

As part of his daily routine, RJ needed to become accustomed to communicating with his clinician nightly, using the modem and the telephone simultaneously. During these sessions, RJ and the therapist discussed and planned future schedules. This process helped to set an example, aiding in prioritizing, thinking ahead, and being realistic about the amount of time needed for various activities. RJ found the convenience of the remote communications to be very helpful. He remarked that it was amazing to be able to relate this intensely to somebody without physical travel. Once he began to use the computerized daily schedule, he became acutely aware of the computer's impact on his daily activities. He stated, "The computer is full of surprises . . . I am feeling more punctual, more on target."

RJ's interactions with the computer became more relaxed and comfortable, and he required less and less supervision. When problems using the software occurred, he was flexible. He demonstrated patience, increased frustration tolerance, and the ability to delay gratification. He became more independent in problem solving, sometimes attempting to circumvent a systems problem with a creative solution. Some of these solutions evolved into new intervention goals. Of paramount importance was RJ's burgeoning ability to be aware of and plan for the future. In just a month after RJ began using the computerized schedule, he was demonstrating the ability to plan social, financial, and medical activities that were two months away.

The computer log report shows that during the first month, he printed his schedule every day. He also checked at least one appointment every day except for one. From a total of 220 appointments during that period, he marked 82% with a check mark to show completion. He also had a total of 402 items on his "to do" list associated with the 220 appointments (the system allowed up to ten "to do" items per appointment). From these, 79 appointments had at least one "to do" item associated with them. He marked 84% of the "to do" items as completed or canceled.

RJ's ability to focus on relevant details improved steadily. He was impressed with his ability to take note of what was on the screen, what used to be on the screen, and what ought to be on the screen. Likewise, the structure of the schedule helped him to focus on one activity at a time and caused him to improve his compliance with and punctuality for appointments. He mentally divided the day into "target zones," a portion of the day which, in his mind, enabled him to refocus and redirect his energies at the start of each new zone, giving him several fresh starts per day.

The Savkin Neurobehavioral Function and Activity of Daily Living (ADL) Rating Scale[29] was used to evaluate RJ's functioning before and after the computer intervention. RJ made consistent gains in executive functioning, such as focusing on a task, decision making, planning, initiation, and cognitive flexibility. Improvements were also noted in RJ's memory for new and important information.

RJ was able to step back from his own success and see himself as part of a team. This was in contrast to his long-term, post-injury personality, where he tended to shy away from social interactions, particularly when new situations and strangers were involved. He dubbed his newfound group "The Cognitive Pioneers of the Future." He envisioned the innovations which evolved from the research as "rehabilitating stepping stones to help others discover a more organized way tomorrow."

Subject 2: "SC"

SC suffered multiple injuries, in a work-related accident in March 1987, when a heavy object fell on her head. SC experienced a brief period of unconsciousness and was diagnosed as having had a concussion. A neuropsychological evaluation in February 1989 revealed a moderate impairment of cortical level functions. Areas of neuropsychological impairment include: significant difficulties in nonverbal abstract reasoning and cognitive flexibility, problems in visual tracking and sequencing, and construction dyspraxia, dyscalculia, left hand motor slowness and weakness, and mild semantic memory deficits.

Following SC's head injury, she underwent a dramatic personality change. She had been personable, friendly, and was a woman of many interests who enjoyed adventures and challenges. However, five years post injury, she was anxious and fearful, with serious initiation problems, particularly during unstructured times at home. She felt the loss of self-esteem, self-confidence, and identity.

Within the confines of the therapeutic situation, SC demonstrated gradual improvement in certain areas, such as increased frustration tolerance, greater carry through, improved memory, and increased willingness to try new cognitive tasks. However, left to her own devices, she was inactive until someone else initiated a task. Although compliant with keeping a schedule of things to do, she would accomplish little in her home. Weekends were especially void of structure and activity.

SC's therapist had been searching for a way to extend the benefits of her sessions to her home environment. It was essential that the initiation problem be addressed if she were to make further progress. The initial goal was to have her initiate a designated daily activity after an external cue; a provision was also made for her to initiate the activity spontaneously. To help orient her, a brief daily schedule would appear on the computer screen including the time that her target activity would be taking place. This activity would be randomly selected by the computer from three familiar games. A CBCP could allow the therapist to "be with" the subject whenever she was at home. By taking advantage of her love of music and color, the computer could cue her into action by an audio prompt (a favorite hymn), and colorful visual prompts with a message of welcome. In order to activate the game, the screen prompted her to strike a clearly marked function key. The computer applauded her efforts thus far by playing a fanfare and then beginning the game.

It soon became obvious to SC and the clinicians that there was a need for an even more engaging activity. Since SC enjoyed writing, a logical choice was the addition of a word processor to her system. SC wrote, "This is the first thing that I can control and no one can tell me about this computer. I call it *my* computer and it feels good."

Improvement was noted in the following areas: frustration tolerance, comfort level with strangers, cognitive flexibility, enthusiasm for cognitive tasks, self-esteem, ability to be a part of a cooperative effort, decision-making skills, assertiveness, trust, patience, ability to evaluate, willingness to seek out challenges, and ability to generalize. The gains achieved through the use of the word processor included finding new uses for the word processor, beginning a memoir, and transcribing minutes of church meetings.

According to the computer log, during the first week she initiated the activity each day on cue. In addition, she spontaneously initiated the activity a number of times each day. At the end of the first week, the goal was considered achieved. During the first month, the target activity was performed all but two days, a compliance rate of 93%.

The Saykin Neurobehavioral Function and ADL Rating Scale[29] was used to evaluate SC's functioning before and after the computer intervention. According to the results of the Saykin Scale, SC made consistent gains in such areas of executive functioning as decision making, ability to focus on goals, ability to shift easily from one activity to the next, and self-awareness of problems. SC also demonstrated progress in remembering commitments and tasks.

Subject 3: "DS"

DS sustained a mild head injury in a motor vehicle accident in March 1991. She experienced a loss of consciousness for several minutes and awoke dazed at the scene. She was taken by ambulance to a trauma center where she was examined, X-rayed and released. Persistent symptoms of pain, confusion, and hearing loss in the left ear prompted her admission to a hospital a few days later. Additionally, DS reported that she was walking into walls, had extreme dizziness, vertigo, headaches, and was unable to drive. Computed tomography scans of the head and an electroencephalogram were performed, and the results were unremarkable. Following her discharge, she continued to have dizziness and persistent headaches, slept most of the day for three weeks after the accident, and reported having dense anterograde amnesia. In May 1991, DS underwent neuropsychological assessment. The results revealed impairments associated with a left hemisphere involvement. Deficits were noted in orientation, attention, concentration, short-term recall of verbal material, immediate recall of visual material, and bilateral pure motor speed. A follow-up evaluation in March 1992 indicated continued mild deficits in concentration, vigilance, freedom from distractibility, remote verbal memory, new learning of meaningful and rote auditory verbal information, resistance to proactive interference, reading speed, reading comprehension, and bilateral pure motor speed. There were indications of continued very mild cerebral dysfunction, largely involving white matter pathways.

At the time of the accident DS was in the final stages of her professional training. She was expected to assume a great deal of responsibility with minimal supervision. Her duties required her to follow complex sequences, process multifaceted information, and readily access isolated facts from memory for problem solving. Given the exacting nature of her profession, she was under a great deal of pressure to perform without error. In addition, her cognitive deficits impacted on some day-to-day functional areas, like bill paying, managing her money, keeping track of appointments, and remembering things she had to do. Worrying about these functional problems was distracting and depleted her emotional and physical energy.

She was very open about her deficits to her friends, colleagues, and teachers. Despite DS's cognitive deficits she retained a normal personal appearance. She continued to display her friendly, engaging personality and did not manifest any outward signs of her compromised functioning. Thus, friends, colleagues, and some medical professionals had difficulty accepting her complaints. Friends were glad to provide help when she requested it, but few realized the severity of her need for help. DS devised a number of manual systems to help compensate for her deficits but these systems proved inefficient and cumbersome, and the disparate pieces were misplaced daily. How long could she continue this way before her career was jeopardized?

The therapist felt strongly that a CBCP would provide DS with the type of organizational structure that she needed. It was necessary that DS have the prosthesis with her at all times, including on the job. Therefore, a lightweight portable computer (notebook) would best serve her purposes. DS became enthusiastic about the idea of a CBCP. It restored her hopes of being able to function closer to her premorbid level. DS and the therapist concurred that, since a prioritized daily "to do" list was of paramount importance, it should be the first system developed for the computer. It was important that DS not only be able to record things she had to accomplish, but also be able to prioritize. Prioritizing an entire list was particularly problematic for her, but she had no difficulty adjusting one priority at a time. DS took control of the design of her system and expressed very definite ideas about how she wanted the software to meet her needs and what the format should be. In effect, she told the clinician and the computer scientist to move aside and said, "I want to design this." Guided by the clinical output of the therapist and the technological expertise of the computer scientists, her specifications were translated to the computer screen. One requirement was that the items appear in a linear format. This facilitated her making adjustments in their rank. When further detail was necessary for a particular item, there was an option to elaborate on another screen. She could also store and retrieve important addresses and phone numbers. Despite the number and complexity of the options available on the system, each screen display had to be clear and simple as DS tended to become distracted by visual clutter. DS's familiarity with a commercial word processor and ability to follow keyboard commands eased her transition to the computer format. DS began using the prosthetic software successfully from the day it was delivered.

DS then asked for a computer-based method of "case tracking" to help her organize at work. The system would allow DS to systematize and access pertinent information about specific cases. Again, DS took ownership of her system and enumerated her specifications. Whereas it would have taken a very long time to develop a successful manual system, the CBCP was completed in only one-and-a-half days.

Overall, the cognitive prosthetic approach gave DS a jump-start, and cut straight through many months of trial and error with manual systems. For this subject, the CBCP served as an important aid for restoring a sense of organization to her life, helping her to set priorities, and aiding her memory. Additionally, the computer helped her gain a sense of control over the day-to-day functional tasks that had been so distracting for her. She expressed her happiness at having a system that satisfied her needs. Of profound importance was the renewed sense of hope that the CBCP generated in her. The knowledge that there was hope made a significant difference in her treatment.

The computer log shows that over a period of 50 days she used her system 45 days (90%). She entered an average of three priority items to her "to do" list per day. She edited and removed some priority items, and added reminders in the form of memos. The case tracking system, used in her work, was delivered about two weeks after her "to do" system. She kept track of 10 cases in one monthly period. Detailed memos about progress for these cases were also kept.

The Saykin Neurobehavioral Function and ADL Rating Scale[29] was used to evaluate DS's functioning before and after the computer intervention. According to the results of the Saykin Scale, DS made consistent gains in executive functioning such as, decision-making skills, focusing on goals and carrying out a plan, initiating, and shifting easily from one activity to the next.

Therapists' Assessment of the CBCP

Over the years, each therapist had envisioned ways to take their patients beyond the limits of traditional cognitive therapy. Creativity, customized materials, and tenacity were not enough to accomplish this. The opportunity to incorporate the use of a customized, CBCP intrigued them. It was a very gratifying experience to collaborate with the computer scientists in the designing of customized computer software that addressed the subjects' needs and their treatment goals.

The CBCP empowered the clinicians to catapult the patient toward many goals at an unprecedented rate. Through the remote control software and telephone hookups, the normal boundaries imposed by office hours and patient appointments were no longer impediments. The CBCP allowed the therapists to provide interventions at any time. It permitted the therapists to enter subjects' environment and monitor progress, impose structure, ameliorate problems, provide encouragement, and gain a better sense of control over the subjects' treatment. The presence of the cognitive prosthesis served to remind the subjects of the behaviors that would help them to achieve success. The therapists were able to gain a better appreciation for the context and details of the subjects' lives. They were able to observe increasingly finer details about the subjects that would not have been learned otherwise, and incorporate this information into their treatment plans. One of the results of all of these advances was an increase in the clinicians' confidence in their ability to make a significant impact upon their subjects' lives.

Within a short time, the feeling of a treatment team evolved. The team included the human and technological partners (therapists, computer scientists, subjects, and computers). Each participant felt very proud of his or her contribution, and the amount that had been accomplished so quickly. A CBCP for brain injury is truly a breakthrough for brain injury rehabilitation.

Software Development Effort

A premise of this research is that an effective CBCP requires substantial customization to achieve a good fit between prosthetic software and the patient. The effectiveness of the CBCP is described above. A major problem in the software field is the amount of time, effort, and staffing required. The iterative nature of our approach required the delivery of many versions of each subject's CBCP. Over the course of three months, two programmers working part-time developed 23 versions of the different systems that were delivered to patients: to gradually increase functional enhancements, to improve the interface, and to remove errors. A total of 389 software components were modified to achieve customization for the subjects. In most of the components, more than one design parameter was customized, so this number understates the extent of customization performed in achieving rapid resolution of functional deficits.

The final applications delivered were: daily schedule, daily "to do" list, music composition editor, priority list, rolodex, word processor, case tracking, and DOS program execution. The three final CBCPs required a total of 21,000 lines of computer code.

Participatory Design

The qualitative impact of the subjects' role in designing their CBCP is described in the case studies. In quantitative terms, the subjects requested changes in 155 of the 389 components, or 40%. It is clear that at least some of the changes would not have been suggested by either the therapists or computer scientists because those changes were either counter-intuitive or violated accepted guidelines. However, the opportunity to have their ideas implemented in computer software had an impact on both patient and therapist. This impact cannot be overstated.

DISCUSSION

The results of this study substantially exceeded its objectives. The most important results were in patient improvement. This field experiment involved three subjects whose rehabilitation progress was slow or minimal, who were more than a year post injury, and whose previous therapy had failed to achieve the goal addressed in the study. Each of the three subjects experienced functional restoration of the elusive rehabilitation goal within one or two weeks of receiving the CBCP. The study was expanded to allow for additional intervention goals during the field experiment period of 12 weeks. The interventions involved a broad spectrum of cognitive deficits including temporal processing, impulsivity, memory, initiation, organizing, prioritizing, and visual cuts.

There are several reasons for having confidence in the results for the targeted activities. First, there is a body of knowledge to explain the results: the experimental intervention was based on the application of computer science principles to the field of cognitive rehabilitation. Second, the results were attained by each of three subjects, acting as replicates of each other. Third, the results were achieved quickly, reducing the likelihood that other influences and situations were the causal agent. Fourth, the results were functional, a readily observed and significant activity recurring in the subject's life, evidencing ecological validity.[30]

The therapists reported, in their progress notes, observing a generalized increase in cognitive function. Because this type of result was not anticipated in the study design, adequate experimental controls were not in place. The issue of a generalized increase in level of functioning will be explored in the next phase of this research, which is currently in progress.

Computer technology extends the therapist's ability to work with the patient, and vice versa. Using a modem and special communications software, the therapist can have a telephone therapy session with the patient. This enables them to have sessions in-between regularly scheduled sessions in the therapy suite. The therapists reported that this capability enabled them to have a greater knowledge of the details of the patient's daily life. During sessions in the therapy suite, telecommunications also enabled the therapists to work directly on the subject's computer, so that when the subject returned home, there could be continuity. Finally, telecommunications access enabled the therapists to better monitor patient progress through access to computer logs and subject's work.

This study adds evidence of the effectiveness, and perhaps necessity of highly customized prosthetic software even for very high functioning patients, such as Subject 3. This subject used commercial software premorbidly, as well as at work during the study period. While the use of commercial software was not attempted for the remediation of the goal, the design of the CBCP for both interventions had features unlikely to be found in a single commercial package. Glisky[5] has demonstrated that, with months of specialized training, even severe amnestics can be trained to use commercial software for targetted everyday activities. However, commercial software does not have the logging and tracking capability that are included in the design of the Institute for Cognitive Prosthetics' CBCPs.

Adapting concepts from computer science to cognitive remediation was a successful approach. The Participatory Design method, rapid prototyping, and user-friendly designs explain and predict the results. Using these strategies increases the cognitive productivity of the user, which is precisely the goal of compensatory strategies in rehabilitation. Other studies that use compensatory strategies, notably Kirsch et al.,[6] and Chute[11] did not apply these areas of computer science.

While computer software is commonly thought to be relatively rigid, this study was able to show that software can be highly customized to the needs of the patient, and that hundreds of design changes could be incorporated into a patient's CBCP. The design and redesigns were ongoing: 23 CBCP versions were produced during the 12-week period of the study, by a staff of two programmers working part-time. This is more than an order of magnitude (10 times) improvement over our initial work just five years ago. This study, which involved three new patients and two new therapists, placed a much greater challenge on CBCP design and therapist training resources than our previous studies. These results suggest that this degree of customization may well be within current industry cost parameters, although such a conclusion requires additional analysis of the data.

Considerable attention was paid to the initial design and testing of the CBCP for each intervention goal in design and testing sessions. Each of the major components of the CBCP was tested by one subject, who would then suggest changes for his or her CBCP. Therapist and subject alike were able to ask for changes in the appearance and operation of the software, and then have those changes delivered within a few days. Many of the changes were subtle, but were obviously important to the subject. Subject 1 designed his system with considerably greater visual subtlety and complexity than anticipated, and then demonstrated its effectiveness in its actual use. Subject 3 was able to play a major role in the design of the prosthetic software for her first intervention, and proposed the design of her second intervention. This means that prosthesis design can and should be driven by patient needs rather than by inventory of computer software modules.

We believe that the patient progress achieved is a result of the proper fit of the CBCP to the subject. We have reported similar results with previous patients.[16–18] Applying participatory design to the development of CBCP interventions is the reason for success of the brain injury patients in our studies. This strategy makes the CBCP faster to design and more effective in outcome. Participatory design does not have to be limited to computer-based systems. In the course of this study, participatory design was applied to several noncomputer components of the interventions.

This study exceeded its goals for achieving an increase in level of function in TBI patients who had been unsuccessful at alternate methods of cognitive remediation. The use of the CBCP technology stimulated enthusiasm among both the subjects and their therapists.

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