Cognitive prosthetics: an overview to a method of treatment

Elliot Cole*
Institute for Cognitive Prosthetics, Bala Cywnyd, PA 19004, USA

This paper is the first survey of the cognitive prosthetics field. Neurorehabilitation based on cognitive prosthetics is now reimbursed as a conventional therapy by many national insurance companies. The need for cognitive prosthetics is described in terms of gaps in rehabilitation methods, and a response to managed care limitations on duration of services. A definition is developed from work in the field, and a cognitive prosthesis is distinguished from both electronic aids as well as from conventional computer software. Some key concepts from computer science are reviewed, along with their significance to cognitive prosthetics. Key studies are reviewed, and show the accomplishments of researchers, differences in their orientation, as well as the impact of computer and communications advances over the past decade. There is a discussion of future research. A key problem is the need to make cognitive prosthetics rehabilitation more user friendly to the therapist. This will be necessary if cognitive prosthetics is to gain widespread use in rehabilitation facilities.

1. The need for cognitive prosthetics

At a recent scientific meeting, a number of attendees had visual problems that affected their ability to see videotape, overhead transparencies and computer output. Several of the presentations addressed use of the World Wide Web by individuals with uncorrectable visual impairments were not presently correctable, and who are unable to see or navigate web windows. Eyeglasses or contact lenses improved many individuals' visual impairments. Other attendees had downloaded technical papers from the web, and had used text-to-speech features of their computer's operating system to preview the paper presentations. Another attendee used a hand-held optical magnifier to view the visuals. Each of these is an instance in which assistive technology was necessary for participation in the activities.

As with visual impairments, individuals with acquired cognitive deficits may need to rely on assistive technology as their only means of performing activities. Some of these individuals become impaired in an instant, through acute processes such as traumatic brain injury (TBI), stroke, brain aneurysm, anoxia, complications of brain surgery, meningitis, encephalitis, and some lesser well known neurological diseases. Still others gradually lose cognitive functioning through Alzheimer's disease or other dementias that produce senility. There are also some neurological conditions that sometimes affect cognition, among them, Parkinson's and multiple sclerosis. Still other people are born with conditions which affect their cognitive functioning. These may range from conditions lumped together as "learning disabilities", through conditions such as dyslexia, as well as various degrees of developmental disabilities/mental retardation.

Part of the process of treating these conditions is the restoration of cognitive functioning to pre-morbid levels. For many people, natural recovery supplemented by conventional rehabilitation will not fully restore cognitive abilities. The rationale for cognitive prosthetics is based on reducing the gap between the recovery that conventional rehabilitation can provide, and the patient's need for functional restoration. In the 1980s, cognitive prosthetics were sought in cases of permanent brain damage, i.e., the inability to achieve functional restoration even after years of intensive and expensive rehabilitation. In today's healthcare environment, the drive for greater efficiency in rehabilitation services and a reduced willingness to fund extensive rehabilitation programs increase the need for cognitive prosthetics.

For individuals who live in rural areas, or in other areas where there is no access to specialized brain injury rehabilitation services, there is a need to receive these services. Computer-based cognitive prosthetics is coupled with telerehabilitation technology for reaching into the individual's home with face-to-face therapy sessions.

*E-mail: ecole@brain-rehab.com.

NeuroRehabilitation 12 (1999) 39–51
ISSN 1053–8135 / $8.00

For career-centered individuals, a high priority is return to work. Time is a key factor: the longer they are out of work, the more difficult it is to return to work. Rehabilitation without assistive technology ultimately may well be successful in restoring their ability to function. However, if cognitive assistive technology can enable the career-oriented individual to return to work sooner, then a significant personal and social need is served.

Technological developments such as the MRI have virtually eliminated the need for exploratory surgery, which was painful and debilitating to the patient, and expensive for payers. The rationale for cognitive prosthetics is driven by similar personal and societal needs. There is a need to speed the recovery process of the patient, reduce the burden on families and other household members, and lower the cost of treatment services. In today's healthcare environment, a premium is placed on rehabilitation methods that cost less and reduce lengths of stay. Many individuals will be denied rehabilitation options that exceed a cost ceiling or take too many sessions to achieve.

2. Defining cognitive prosthetics

Kirsh and Levine [33] developed an early conceptual approach for cognitive prosthetics. They addressed the needs of patients who required cueing by a caregiver in order to perform a target functional activity. A three dimensional framework was developed for categorizing modes of rehabilitation: A *compensatory strategy* (as opposed to a graded drill) that alters the patient's *environment* (as opposed to improving the patient's abilities) and directed to an individual's *functional skills* (as opposed to retraining of component neurocognitive abilities). Cognitive prosthetics was seen as being in the realm of a compensatory strategy which alters the patient's environment for performing specific functional activities. Kirsch and Levine's approach to cognitive prosthetics used computer technology, which was *highly customized* to the needs of the individual patient. High customization was needed in order for the prosthesis to be effective. Each prosthesis would be designed in computer software for a specific individual, performing a highly structured target activity, such as baking, in a particular setting. A therapist would program the prosthesis to display directions for any structured task that involves a sequence of steps. The researchers found that the computerized instructions have to be revised regularly using clinical input based on the patient's capabilities. Further work is required to determine the clinical parameters.

Because of the constellation of deficits so often found in head trauma, Chute et al. [4] suggested that the prosthesis should have the capability of supporting the TBI individual in many activities. This allows for application and data integration, so that compensatory procedures can be coordinated. Equally important, a single computer can make the compensatory tools easier to use by transparently performing some of the necessary tasks and having a common interface style.

Work on aphasics was another backdrop for cognitive prosthetics. Global aphasia is a condition in which the individual is unable to understand written language, unable to understand spoken language, and unable to speak in words. Communication can take place through pictures. Steele et al. [40] and Goodenough-Trepagnier [26] independently developed a computer-based cueing system for global aphasics. Steele developed a microcomputer-based method that enabled a global aphasic to follow a recipe for a cooking task through pictures. This involved highly customized pictorial instructions. This approach changed the environment for the patient, supporting functional activities. Also, this technology needed to be highly customized to the specific patient, the specific recipe, the specific ingredients, and the oven to be used. This was prosthetic in that functional support was provided for functional deficits.

In the late 1980s, Goodenough-Trepagnier [26] developed a computer-based visual communication system (C-VIC) that was implemented on a microcomputer. Using this system, she evaluated whether an individual with severe aphasia was able to communicate in sentences via icons that represented word categories such as persons, actions, or objects. System customization was used to achieve a better match with individual's capabilities. The use of icons changed the environment for this individual permitting some remarkable successes in communication. In order for individuals to incorporate C-VIC into their functional communication repertoire, the technology must be customized to fit each individual's retained abilities and needs.

Cole and collaborators [5–20] have developed highly customized software to enable the performance of specific everyday activities that are patient priorities. A cognitive prosthesis needs to address a wide range of the individual's *priority* functional activities to be valuable. Customization reflects a number of factors: (1) Patient priorities for activities; (2) abilities in context of the environment where the target activity is performed; (3) functional deficits which require support; and (4) features that make the system "user friendly" to the cognitively impaired user, who may also have physical impairments. Prosthetic software is not like a conventional computer application, such as a word processor or scheduler, which offer many features to the user. Rather, prosthetic software fills in for specific functional subtasks, which the individual is not able to perform, and is highly customized.

While the author's cognitive prosthesis *uses* a specific computer platform (currently Microsoft Windows), the prosthesis must be sufficiently flexible to support an individual's activities not only at home, but also in the community, at school, and at work. This requires the ability to integrate diverse hardware and software components, as well as highly customized paper forms. Therefore, a cognitive prosthesis requires extensive customization, typically with more than 1000 parameters. For each patient, the cognitive prosthesis will be multi-functional and integrated on a common platform. Each prosthetic application needs to be specifically customized, and contextual elements of the task and setting are considered. The evolution of an individual's cognitive prosthesis continues over a period of many months as one activity is added to another. The evolution of the prosthetic software is supported by automatic data collection, and is tightly coupled to rehabilitation therapy.

A definition of cognitive prosthetics emerges from this work. A cognitive prosthesis is one of many types of treatment that, in the Kirsch-Levine framework, is a compensatory strategy that changes the environment and focuses on functional activities. A cognitive prosthesis uses computer technology. A cognitive prosthesis is designed specifically for rehabilitation purposes. Functional deficits are ameliorated by changing aspects of the environment in which the patient operates. It directly assists the individual in performing some of their everyday activities. It is highly customizable to the specific needs of the individual. That customization is required to make the individual effective in performing the task. The customization is also required to make the cognitive prosthesis "user friendly" to the patient. Unlike conventional commercial software, it does not provide the patient with additional features which are not clinically indicated. It collects data while it is being used, and that data is used in clinical treatment and ongoing assessment.

The above work provides definitive characteristics of cognitive prosthetics. The following empirical studies offer examples of their uses, strengths and limitations.

3. Empirical studies in cognitive prosthetics

Merzenich et al. [36], and Tallal et al. [42,43] have done seminal work on problems of auditory processing. One aspect of these investigators' work addressed a language-based learning impairment in which individuals are unable to comprehend spoken language because of disruptions to their cognitive processing of sound waves. Tallal et al. [43] identified a neurophysiological basis of the disorder, normal speech was occurring at too fast a rate for the sound processing capabilities of children with this condition. Using a computer algorithm, the investigators were able to "stretch" the sound wave form from 40 to 80 ms, thereby changing the environment to allow for the elongated latency of the patient. In this way, the patient was able to comprehend speech. Hypothesizing the physiological basis of a cognitive disorder, and using it to design a cognitive prosthesis was an important milestone.

Having developed a prosthesis, the investigators have proceeded to address a cure, which applies additional computer-based techniques. Both Merzenich et al. [36] and Tallal et al. [42] have extended this work by applying research in brain plasticity to the auditory processing dysfunction. These authors hypothesized that the dysfunctional neurophysiological parameter could be reset by slowly moving the latency period back to the normal range. Treating children with a language learning impairment, the researchers embedded therapy in a computer game designed to be engaging. The investigators reported that in two studies ($N = 7$ and $N = 22$) some of the patients were restored to normal hearing. The researchers were able to report functional change (children for the first time could understand speech), standardized test change, and neurophysiological change. A larger multi-center study is currently underway [39]. Some of the brain plasticity literature [36, 37] suggests that plasticity can be produced when the individual becomes heavily engaged in a target behavior. This engagement contrasts with mere repetition of the target behavior as is found in many cognitive skill exercises.

Kirsch et al. [32,33] published excellent studies on a cognitive prosthesis conceptualized from a rehabilitation perspective. Individuals with substantial memory and constructional deficits, but with intact language abilities, served as the subjects for the studies. The prosthesis required substantial customization of tasks and task structure, through a programming language that the authors developed for use by occupational therapists. The prosthesis was designed for a very specific, highly structured, patient activity which would be performed in a target setting. An occupational therapist customized the software and assisted the individual in performing a target function. The occupational therapist also provided cognitive support to the individual throughout the activity and in the place where it was performed.

The original experiment was a single-subject case study [33]. The later paper [32] reported on two other cases. In the first, one subject performed a baking task with 15 stages, such as adding water to the mix. The prosthetic application was an instructional module with step-by-step directions, which also kept track of elapsed time so the patient could be interrupted to perform certain tasks. The results indicated that computer assisted instructions produced fewer errors than following standard written instructions. In the second study, one subject was involved in a cooking task and the other subject in a janitorial task. On the cooking task, the subject committed fewer errors with an index card cueing system and a computerized cueing system than with a standard recipe. The researchers could not isolate the success for one or the other cueing systems.

The subject with the janitorial task was able to improve performance using the computer's guidance relative to performance using written instructions. The researchers recommended that further studies should be conducted with more cases to evaluate instruction following. The researchers found that the computerized instructions have to be revised regularly using clinical input based on evaluation of the patient's capabilities. Some patients may not reliably respond to computer cues because of specific impairments. Further work is also required to determine the types of tasks that these systems can best supplement.

Chute et al. [4] provided a neuropsychological conceptualization of a cognitive prosthesis. The research design was a single-subject post-test laboratory design. Unfortunately, the empirical results are disappointing, in large part because the subject was selected shortly after the injury, before a full assessment of the individual's capabilities and resources could be made. The individual was aphasic, without speech, and fine motor skills were not intact, thus placing a further burden on the research design. Furthermore, the researchers originally provided a complex design which had to be simplified to allow their subject to use the system. This approach prevented the isolation of problem factors in the design.

Steele et al. [40] developed a cueing system for the aphasic population. They reported success in food preparation from recipes with the use of customized software on the Macintosh computer. Their subject was a head-injured individual with profound speech impairment and no comprehension of written material. In their approach, the researchers developed pictures of objects (e.g., chef, stove) appropriate to a cooking task and grouped meaningful pictures representing instructions for cooking using the metaphor of a notepad. The pictures representing each step of the recipe were presented in sequence on the pages of the notepad. The subject could move backward or forward through the notepad to gain an overall perspective of the task. Certain cues were provided, such as a hand turning on the stove, to alert the subject to a specific task. The subject was able to follow instructions provided by the computer in eleven of the fourteen trials for six different recipes. The success ratio could be attributed to the appropriate representation of subtasks in pictures and the subject's ability to pace himself through the task. The researchers expressed the failures to be due to a lack of overview for the cooking task (moving back and forth through the tasks sometimes was too complicated for the subject) and the subject's ability to deviate from the instructions based upon expectations.

Parente [38] took a different approach to the problem of cueing for complex activities for individuals with memory disorders. He used expert-system technology to assist the patient in performing highly structured activities. Highly structured activities can be broken down into step-by-step tasks, which have rules for each step. An expert system can be programmed, based on a specific set of rules, to perform certain aspects of a task. He found success for this approach in supporting vocational (clerical) tasks, using an IBM-compatible laptop PC. His approach was to analyze the vocational task. Then a set of rules was prepared to define the task using the First Choice expert system shell software package. The user was given cues on the computer screen, and responded by pressing a single key. He reported that he continued to modify the system for about a month following its initial use by the patient. Parente's approach shares the same goal as Kirsh and Levine in that structured task is being supported. He has gone farther though by supporting the individual at the work site as opposed to in the lab. However, his system was not designed to be customized by the patient's clinician.

Friedman and Henry [27,28] reported a field study on memory aids. A traditional logbook was compared to an electronic memory aid for daily task schedules for a non-aphasic head trauma population. The memory aid was a custom built portable computer with digitized speech output that provided a pre-timed prompt for the subject to perform a scheduled task. The strength of this research was recognizing the need for a memory aid that assists with self-monitoring tasks. They used an alternating treatment design in an inpatient rehabilitation setting. The logbook was alternated daily with the memory aid. This combination of interventions in a research design may have prevented the subject from incorporating the memory aid into their daily behaviors and routines.

Levinson [34] developed a customized system that addressed executive dysfunction, such as planning and self-monitoring. His approach was to use artificial intelligence (AI) technology to implement executive functioning concepts of Sohlberg on a palmtop computer. This AI planning system allowed users with brain injuries (or their caregivers) to define scripts for activities, such as morning routines or going shopping. The user could add appointments, or make adjustments to the scripts, and the system evaluated the plan for conflicts and modified the plan accordingly. Plan execution was assisted by prompting the user with visual and audible cues at each step of the plan. This system was limited to executive functioning, and is not intended to compensate for other cognitive dimensions such as memory dysfunction, which may limit its usefulness in addressing the needs of actual survivors.

Dowds et al. [21,22] have made adaptations to standard software on a palmtop computer. The software was designed to manage scheduling information in order to help memoryimpaired individuals to remember what to do and when. This was accomplished via a text display as well as an audible alarm that went off at the user-selected time. The investigators found that this approach was beneficial to individuals with memory deficits. However their work was limited to the Psion handheld computer platform, and their ability to modify the computer software is limited. This software does not permit automatic data collection on its use or customization of the user interface.

NeuroPage has become familiar to many in rehabilitation in part because of the involvement of Dr. Barbara Wilson in empirical studies. This device delivers an auditory signal and an explanatory message as a scheduling reminder. Empirical results are impressive [29,44]. Subjects could be cued to perform tasks with NeuroPage and showed significant improvement in the percentage of tasks achieved. NeuroPage is assistive technology, not prosthetic technology; its capabilities are severely limited. The empirical results demonstrated how technology could help the individual with severe deficits. These studies are significant because so few international authorities on brain injury rehabilitation have incorporated any technology specifically designed for clinical use.

4. Computer science concepts underlying cognitive prosthetics

Several concepts from office information systems and from human computer interaction have been particularly pivotal in the development of cognitive prosthetics. Most fundamental is a relatively old office automation concept of computer technology as a means of augmenting intact cognitive and intellectual performance [23]. One can then postulate that computer technology could compensate for cognitive deficits.

Office automation has explored cognitive support basically by taking a look at the individual worker's *activities and tasks.* These roughly correspond to the rehabilitation concept of a functional activity, such as making a checklist, or paying bills, or deciding how to prioritize the day's activities. An activity generally is a larger entity, and consists of a set of tasks, which in turn consists of a series of subtasks. An activities-oriented model is very well suited to overcoming rather than curing disabilities, because it is not necessary to identify the cognitive dimensions of the activity in order to overcome a deficit. A cure requires much greater knowledge about the cognitive components of the function.

Activities themselves can be categorized according to the their degree of structure: Structured, semi-structured and relatively unstructured activities [31]. Knowing the type of activity that a cognitive prosthesis is to support has proven valuable in prosthesis design. A highly structured activity is one that can be set out and executed in a step-by-step process. A semi-structured task has some structure, but also is significantly dependent on the context of the task. Thus it is possible to pre-program parts of the task, but other parts require too much contextual information to be able to set out step-by-step instructions. It is, however, possible to develop applications which provide substantial support for semi-structured activities. Many higher-level problem solving and analysis tasks are semi-structured. A relatively unstructured task lacks most structural elements. A set of very general tools can often be used to provide computer support for relatively unstructured tasks. A cognitive prosthesis can support all three types of activities, and, of course, the nature of that support will be different.

Usability becomes a fundamental concept and requirement for prosthetic software design. In the mind of the general public "user friendliness" is an attribute of a device. As specialists, we understand that usability describes a relationship among user characteristics, task characteristics, and device characteristics. There are multiple and conflicting performance criteria. What is "user friendly" to an individual with cognitive disabilities (and to the larger population) in one circumstance can be user hostile to the same individual in other circumstances.

Finally, implementation details are critically important to system success and acceptance. Interface design, in particular, is largely dominated by many minute details. Furthermore, the context and content of the application complicate the adherence to a single "style" of interface or a simple set of standards. In the cognitively impaired individual, the details take on added importance. These must be designed so that the application is both understandable and user friendly to that individual. Typically this involves design and testing at a level of detail which most therapists never encounter in their personal and professional lives.

5. Research and clinical approach at the Institute for Cognitive Prosthetics

In the mid-80s the author toured a residential brain injury rehabilitation program. A high percentage of the clients were several years post injury, were unable to live independently, and had little prospect of further significant recovery. The author hypothesized that concepts from computer science could help this type of client achieve increased self-sufficiency. Initial research was funded by insurance companies, and by grants from the National Institutes of Health.

The broad objective of our work at the Institute for Cognitive Prosthetics has been to help disabled individuals achieve greater self-sufficiency through the use of Computer-Based Cognitive Prosthetics (CBCP). Our clinical research and development approach has been the single-subject case study. Single-subject case studies [2] have been traditional in brain injury rehabilitation research because each individual's combination of cognitive abilities and deficits is virtually unique. In the single-subject design, each subject serves as his/her own control.

A subject selection criterion required a post-injury time greater than the period in which spontaneous recovery could medically be expected. For TBI this period is about 18 months, and for stroke 9–12 months [3]. After that time, traditional rehabilitation could produce increases in the individual's level of function, but the rate of increase is slow. Eventually, the rehabilitation progress plateaus. Individuals recruited as research subjects have had cognitive rehabilitation, and have plateaued for those rehabilitation goals which were set for our studies.

In each case, baseline data demonstrated that the individual was not able to perform a target activity self-sufficiently prior to the intervention. Researchers or therapists then describe the target activity in functional terms and often also in terms of the cognitive dimension(s) which may be impaired. Prosthetic software is designed to bridge the functional deficits, often at a minute level of detail. Considerable usability testing is involved in preparing prosthetic software for the patient. Cycles of redesign and testing take place, until the individual is capable of performing the activity with the assistance of the prosthetic software. Improvements in functioning following the commencement of our treatment could be attributed to our treatment. These improvements are often seen within a few days.

The original standards for usability were:

- Using the software without becoming too confused
- Being able to continue after making an error in software use
- Being able to complete the target activity with the use of the prosthetic software
- Attaining the above goals with less than three half-hour training sessions required

Once standards for usability are met, the system is installed in the individual's home, and the treatment begins. The treatment consists of therapy coupled with the use of prosthetic software. After the initiation of treatment, the prosthetic software is fine-tuned with regard to both functional requirements as well as interface features. The intervention is deemed a success when the individual is able to perform the target activity self-sufficiently without the aid of a caregiver.

The following case studies illustrate a sampling of prosthetic applications developed to address different rehabilitation goals. These case studies will also summarize some of the notable improvements in functioning with the use of the CBCP, as well as salient clinical observations.

6. Case studies utilizing computer-based cognitive prosthetics

IE, a 50-year-old woman, was involved in a minor automobile accident. Initially she suffered bruises, but over the next few days developed a number of serious cognitive problems. She had a profound short-term memory loss, an inability to sequence subtasks in an activity, and was also diagnosed with a "left neglect" (inability to process information on the left side of the visual field). She also had an apraxia, which interfered with some fine motor skills in her left hand. For 3.5 years she received extensive therapy, but was still cognitively impaired to the point of needing a full-time aide. For two of those years, she was given twice-weekly training on a checkbook program and a word processor, but was unable to use either without someone standing over her. She had over a dozen therapists serving her.

Her priority target activity was to pay bills. The initial cognitive prosthesis chosen to address this priority activity was a check-writing application. The goal was to develop only the necessary functionality to accomplish the target activity, with a human-computer interface that met several usability requirements:

- ability to pay bills at any time without the active involvement of caregivers
- no confusion as she progresses through the software
- eas4y to learn
- errors easily corrected

There were many usability testing sessions, which focused on each interface component, and then on major sections of the software. It took about 10 months to build, and required creating or changing over 1000 interface and functional parameters.

The computer system, including a printer and a dedicated phone line for a modem, were installed in the patient's home. After installation and initial use, modifications were made to the software. There needed to be modifications to the interface and system functionality which became evident only after a period of use by the patient. Some of these user requirement changes were needed to achieve system performance standards. Other changes were requested by the patient, which increased user satisfaction. An important class of changes was the enhancements, that increased the functionality of the patient's system. These were suggestions by the patient for increasing the utility of the prosthetic software. Some increases were suggestions for new features to existing software. In other cases, new types of activities required new application software.

Three additional major modules were added to the patient's system. One was a primitive text editor, which had print, save, retrieve, and exit features. Another was a schedule which contained some daily information, including the time and menu of lunch and dinner.

Several outcomes were significant. First, the software was prosthetic; it provided cognitive support for specific subtasks of the target activity that the user was unable to perform. She no longer required a caregiver for assistance in these activities, although caregivers were necessary for other activities. Second, the system was a multi-functional prosthesis in that there were several different prosthetic applications, and several different types of personal activities which these systems supported. Third, this individual with a profound memory loss was able to learn how to use the interface with less than three half-hour training sessions. Fourth, considerable customization was necessary to be successful. Fifth, customization was most successful when applied to the specific instance, rather than based on broad principles. For example, there were considerable differences in the amount cognitive information (chunks) that were required to support different subtasks. We had anticipated greater consistency in the amount of cognitive information which the individual needed. This case was reported in Cole and Dehdashti [18,19].

EV, a high achieving 34-year-old woman, had a series of strokes, which left her with substantial physical and cognitive deficits. She was reduced to no use of one hand and only limited motion and digit control of the other. She was unable to independently perform many activities of daily living and had to depend upon caregivers for assistance. Written expression was very important to her, but writing was both painful and tedious. She was unable to read more than a few sentences at a sitting due to visual scanning difficulties.

The initial intervention goal was to express herself in writing, using a text editor with a password. A password was necessary to assure that her writings would be private. Software usability testing was difficult because her test-retest reliability was poor; similar results were seen in her neurological evaluation. Although neurologically compromised individuals can show very substantial variability in performance, this case had notable variation unrelated to fatigue. The prosthesis designed for her was simpler than the one built for Case

IE above. This was surprising because EV's memory appeared to be considerably less impaired than IE's. The initial design had menu commands Print, Save, Retrieve, and Exit implemented as Function-Key commands. Three punctuation marks were implemented as remapped lower-case keys: exclamation point, question mark, and double quotes. The patient requested this in order to use these punctuation marks with a single keystroke. Document names could be as large as 60 characters, but typically were just a few words. Documents were automatically saved to prevent loss of work, and when the user did not give the document a name, a default name was used. After a few months, a cut and paste feature was added at the patient's request. Two other major applications were added. One was the American Heritage Dictionary. This had both a dictionary/definition feature and a thesaurus feature. This provided intellectual stimulation as she "surfed" words and their definitions. A second application was a paint program, which required the introduction of a mouse (Kinsington "Mouse" trackball). After about six months she attempted but failed to learn Adobe Illustrator.

After two years of using her evolving prosthetic application, EV began using off-the-shelf software: Microsoft Word, America Online (AOL), and Netscape Explorer. She is able to use the most basic features of Word. She spends a substantial amount of time using the Internet via AOL, including chat rooms and email.

This case is significant for the profound impact of the intervention on patient functioning. Perhaps the clearest evidence of this is her change in reading. Over a period of just two months, EV went from being able to recognize half the words on a line when double-spaced to recognizing 95 percent of words single spaced. She also went from having a reading endurance of about two paragraphs to being able to read 100 pages in a day. Other changes included an improvement in spelling and grammar, a substantial reduction in impulsivity, an increase in concentration, an ability to grasp "finger food" such as a sandwich and chips, and increased ability to dress herself. All of these occurred over a period of two months after the start of her intervention.

This case is also significant because the patient has ultimately and successfully moved from our highly customized software to commercial software. The first attempt at commercial software in the first few months after commencement of treatment was a failure. Two years later there was success. At least some of the difference should be attributed to an increase in cognitive functioning. Some of the difference can also be attributed to acquiring computer knowledge and skills. This case was reported in Cole et al. [16].

CS, a 61-year-old man, who was a very successful senior executive, sustained a head injury in a bike accident. Neurological examination and neuropsychological assessment revealed that CS suffered anterograde and retrograde amnesia as well as impairment in prospective memory. He also exhibited problems with attention and concentration, visual-spatial processing, and global executive dysfunction.

Because of persistent problems with disorientation and memory, CS required moderate supervision by family members day and night. Initial evaluation of CS at home revealed that, although he understood that a number of people had, and would be, telephoning or visiting him, he was unable to keep track of these encounters. His first rehabilitation goal, therefore, was to orient him to social contacts. His CBCP would remind him of phone calls already received and those expected. Such knowledge was of primary importance in helping him regain control over a portion of his life. His CBCP eventually helped him to keep track of other daily activities and responsibilities.

There are several aspects of this case that are significant. First, the CBCP worked for him as the initial outpatient treatment. This required that design and customization be produced in a timeframe of hours to days, i.e., fast enough to be used on an individual whose cognitive functioning seemed to be changing rapidly. Second, the initial application was directed toward a very narrow functional requirement, one which was met by many scheduling and daily-diary applications. The patient wanted only minimal functionality. Third, it was an anomaly that he was able to perform extremely demanding cognitive tasks while unable to perform other tasks which would be judged much simpler cognitively by unimpaired people. He could negotiate projects involving millions of dollars, which were both intricate and difficult. However, he was unable to organize his own bills, and he found supermarket shopping too cognitively demanding to do successfully without the use of the CBCP.

RE, a woman in her mid-thirties, a high school graduate. She was two years post TBI, and referred by her occupational therapist. The patient scored in the highest range on occupational therapy functional evaluation scales in the clinic. Yet, this woman was failing in a number of everyday activities in the home setting. This included an inability to keep appointments for herself, and for her young son who required ADHD-type school services following the same accident that injured his mother. Other problems involved inability to follow recipes, and difficulties in organizing and paying bills. She was also unable to do her crafts which had been a creative outlet for her before her accident. Neuropsychological evaluation revealed problems in memory and executive functioning, primarily in planning and organization.

The initial intervention was a daily schedule application with minimal features for usability, but sufficient for addressing targeted activities of meeting daily obligations. Initial features included setting a schedule item, adding a detailed memo to the item, printing the day's schedule, moving to another date, and exit. The prosthetic software was quickly designed. The computer and printer along with a modem and dedicated telephone line were installed in her home. Her therapist worked with her daily, guiding her in the structure of her day. These therapy sessions involved talking on a voice line and working on the computer with remote control software. This software allowed her therapist to observe the patient's use of the prosthetic application. The patient achieved success in meeting her obligations with the use of the application during the first week. Next a simple text editor was added. Again, it was quickly designed. In less than a week, she was using the text editor to organize tasks for herself and her son with relatively simple lists.

This case focused on a person who was not so disabled that she required a caregiver, but who was sufficiently disabled that she was unable to successfully perform typical everyday activities. Often these "high functioning" individuals are difficult for traditional rehabilitation programs to treat. For this patient, rather minimal functionality was used very extensively to provide organization and structure. It was notable that the simple text editor enabled her to prepare a well-organized list, when compared to pencil and paper methods. Word processors uniquely enable the individual to move around the document and thus are able to support a disorganized thought process.

Dr. T: Dr. T was in his early-50s when coworkers became aware that he had profound memory and organization problems in the hospital. His was a fast-paced hospital-based practice, and he was unable to track the status and treatment of the several patients in his care at any minute. Neurologic evaluation initially suggested Alzheimer's, but the diagnosis was changed to dementia of unknown origin. Dr. T resigned from his position.

On clinical testing, he was unable to remember any new information after 30 minutes. He needed to be reminded of activities and appointments during the day. As a doctor he was used to carrying a pager; now, he would use one to remind himself of his activities. A scheduler with a pager was customized. Dr. T would be able to plan his day on his computer and send himself reminders at specified times. The pager enabled him to send himself an 80 character alphanumeric message. It was interesting that he was able to give himself this short cue which would enable him to perform a more complicated task. His schedule software had basic features of adding a scheduled item, providing extended details of the item, setting the time and message of the optional page, printing the daily list which included the item, the details, the beeper time, and beeper message.

He was able to track and perform his scheduled activities in less than a week using his prosthetic application. He used this over a period of about six months, after which his functional memory had improved, but was still in the impaired range. The improvement was attributed to his substantial reduction in cognitive load following his retirement.

This case was significant because of the beeper's ability to initiate action at locations away from the workstation. This kind of capability is now a standard component of our capabilities, and is being used by a wide range of patients. This case was described in Hoepfer [30].

6.1. Pooled case studies

This study raised three broad issues. First, could CBCPs be effective in increasing the level of functioning for what therapists consider plateaued and dead-end patients. Second, can the design of CBCPs be automated so that prosthetic software can be quickly customized. Third, to what extent can cognitively disabled individuals participate in the design of their prosthetic software. In an NIH-funded study, seven of nine plateaued patients were able to achieve a priority activity in between one day and three weeks of use. For three of the patients, 23 systems and versions were produced over a 12-week period. Changes were made to 389 software components (functions). It was found that participatory design has many benefits with CBCPs. Patients can often provide solutions to functional and interface problems with their systems. In this study, patients made 46% of functionality design/redesign recommendations, and suggested 42% of the interface changes. Participatory design is particularly useful in resolving relatively fine-level implementation details. Early cases in this study were reported in Cole et al. [11–17].

6.2. *The current state of cognitive prosthetics*

Over the course of a decade, a new field has emerged. A number of technological advances have been attained, and a number of important milestones have been met. These are very exciting times for cognitive prosthetics.

In the current healthcare environment, a most important milestone to achieve is the reimbursement by national insurance companies as a conventional rehabilitation service. This milestone was achieved in the mid-90s for the treatment of cognitive deficits from diagnoses including traumatic brain injury, stroke, brain aneurysm, solvent encephelopathy, and early onset dementia. In most instances, this reimbursement was for telerehabilitation services, i.e., services which were delivered directly into the patient's home, office, or rehabilitation facility. Cognitive prosthetics is now prescribed by physicians as an accepted medical procedure.

A decade ago, work on cognitive prosthetics was focused on proof-of-concept, and was narrowly applied in terms of clinical criteria and in terms of technological capabilities. Currently, cognitive prosthetics can address the self-sufficiency needs of a broad range of activities. The strategy is to build "one-of-a-kind" systems using a highly flexible software development environment. The approach of "one of a kinds" enables the cognitive prosthetic practitioner to be able to serve the needs of the individual patient, as opposed to only providing support of a limited set of functional activities currently available in a software inventory.

Cognitive prosthetics is made possible by the many technological milestones in hardware, software, and communication technologies. A decade ago there were microcomputers, with one program (windows) running at a time, 2.4Kb modems, and no World Wide Web. Today, microcomputers are not part of the vocabulary, because today's hardware has the capabilities of many mainframes of the 80s, and palmtop computers with unimaginable capabilities from an 80s perspective. Today's software development tools have changed the way programs and designed and written, and have tremendous capabilities, compared to a decade ago. Communications have changed, with mobile computing linked to cellular networks, cable modems widely available at speeds of 1.5 Mb, and telephone modems running at 56K. These advances have the potential of continuing to reduce the complexity of cognitive prosthetic implementations, and at the same time reduce the cost of the assistive technology.

7. Directions for future research

Rehabilitation technology has enormous potential, and there are many possible avenues for future research. However, several stand out because of timeliness, current activities, or, in the case of the first to be discussed, because of its importance to the dissemination of this technology.

7.1. *Making cognitive prosthetics more user friendly to therapists*

Cognitive prosthetics has many significant benefits for the patient, but currently places a significant burden on the therapist. Cognitive prosthetics makes substantial changes on the method of treating patients. This means that there are new technologies to learn, and added tasks in the therapist's workload for each patient. If a substantial number of therapists are to adopt cognitive prosthetics as part of their professional repertoire of tools, this assistive technology will need to become more user friendly to the therapist. A similar technology, which is a decade older, faces similar problems and may productively serve as a model.[1]

Cognitive prosthetics adds to the tasks that are involved in treating the patient. The treatment model is an extension of community-based programming, which focuses on patient priority activities. These activities are best performed in the patient's own setting. These are among the more significant changes:

- Decide which subtasks to retrain and which to bridge with a cognitive prosthesis
- Specify the functional requirements of prosthetic software

[1] It is useful to look for a model which may provide some guidance in how these issues have been addressed. The closest "relative" to cognitive prosthetics is alternative and augmentative communication (AAC), which is about a decade older than cognitive prosthetics. AAC uses complex computer technology, and is appropriate for individuals with diagnoses which are treated in rehabilitation hospitals. Yet, AAC has made few inroads there. AAC is rarely found in even the tertiary rehabilitation facilities. This can be attributed to AAC being relatively "user hostile" because of the added work load requirements, and rigidity. Instead, AAC is available through other channels, such as state assistive technology programs, and special education programs. The training requirements for treating a patient with AAC technology are substantial. Technology is often very rigid, increasing the difficulty of treating patients. These problems now tend to fall on the shoulders of the therapist. One can understand then why AAC technology is so rarely available in the "conventional" specialized rehabilitation facilities.

- Learn certain software development methods such as participatory design and evolutionary design
- Train patients to use their prosthetic software, including providing user support
- Fine-tune prosthetic software designs
- Conduct usability testing
- Customize certain software and interface features
- Adjust treatment preparation to include new types of data collected by the patient's prosthesis
- Use a new software system designed to meet the needs of therapists who treat their patients with cognitive prosthetics
- Optionally use communications hardware and software for telerehabilitation sessions with distant patients

The brain injury rehabilitation literature and conference proceedings are significant for the lack of studies and investigators in assistive technology generally. Indeed, it is noteworthy that technology plays such a minor role in brain injury rehabilitation compared to so many other disability areas. One explanation is that the assistive technology, which has been developed, is not yet sufficiently "user friendly" for transfer from technology developers to widespread clinical use.

7.2. *Computer software's impact on neurophysiological functioning*

There is some preliminary indication that under certain special conditions, some prosthetic software technology has demonstrated an ability to produce a "cure", sometime eliminating symptoms, and other times greatly reducing them. Merzenich [36], Tallal et al. [42], and associates developed an auditory prosthesis which was able to "reset" critical neurophysiological parameters for some subjects in small-N studies. Resetting these parameters appeared to produce a "cure" for the disorder in some of those subjects. The significance of this study is enhanced by the strong theoretical framework underlying this research.

The mechanism hypothesized for "resetting" the parameters is brain plasticity. Merzenich proposed that brain plasticity can result by the individual becoming engaged by the cognitive prosthesis. He developed an intervention for children masquerading as a computer game which absorbed the attention of the child. He suggests that it is engagement, rather than repetition and compliance, which is a critical factor in exploiting brain plasticity. Aftonomos et al. [1] has reported significant recovery of expressive and receptive language in patients who had been global aphasics. Cole and associates have reported two instances in which patients have demonstrated what appeared to be an unexpected reduction in symptoms accompanying their embracing the cognitive prostheses [11,18]. Brain plasticity provides a theoretical basis for what otherwise seemed to be curious anomalies.

Brain plasticity is a relatively new concept [24,41]. Stein et al., for example, believe that brain plasticity may have some importance for brain injury rehabilitation. Optimally configured cognitive prosthetics may well have the qualities which are conducive to plasticity mechanisms. There would seem to be several avenues for neuroscientists to explore, including the use of functional MRI along with cognitive prosthetics.

7.3. *Out-of-sequence rehabilitation*

A cognitive prosthesis can enable a therapist to address rehabilitation needs out of the sequence normally imposed by the retraining paradigm. This is practical because a cognitive prosthesis can bridge functional deficits. There are a number of instances where this is highly desirable.

For some individuals, especially career-oriented individuals, time is a very significant factor in successfully regaining important aspects of their lives. CS was such a case, where he was a senior manager, and a prolonged absence from work would require someone else assuming his work responsibilities. He was able to return to work before many key community-reentry skills had been introduced let alone acquired. In this case, difficulty with some key community-reentry skills would have greatly increased the time he was away from his job, making return to work all the more problematic.

Out-of-sequence rehabilitation has many advantages in an era of managed care restrictions on length of stay. If rehabilitation is left intentionally incomplete, aspects of rehabilitation can be more attuned to patient priority activities as they develop in the everyday environment. Cognitive prosthetics makes this attainable.

7.4. *Telerehabilitation and cognitive prosthetics*

There is a natural synergy between cognitive prosthetics and telerehabilitation. The integration of these technologies provides the therapist with powerful tools to address the challenges of the 21st century. The article by Rosen in this issues provides a thorough description of telerehabilitation.

8. Conclusion

Cognitive prosthetics is a complex technology which is capable of providing functional support for neurorehabilitation patients with cognitive deficits even when accompanied by very substantial physical deficits as well. Cognitive prosthetics takes advantage of microcomputer and communications technology; as a result, patients can be treated in the home or office from a distant facility with face-to-face therapy sessions. While there are somewhat different approaches among prosthetic designers, the common approach is functional support of everyday activities. Because a cognitive prosthesis can bridge a patient's functional deficits, it is possible to address functional goals out of conventional sequence. This has important implications for accelerated return to work or return to school. An important area for future research is making cognitive prosthetic software more user friendly for therapists. Cognitive prosthetics is probably the most complex assistive technology, and assistive technology generally has been very slow to take hold in rehabilitation facilities. As the most difficult case, there are advantages to focusing on usability issues for cognitive prosthetics first, and then addressing the cases of less demanding assistive technologies. Recent work combining computer software with brain plasticity models has produced promising initial results. This work raises many important issues.

Acknowledgments

This research is funded in part by NIH Grants NS27898 and MH59012.

References

[1] Aftonomos, Lefkos B., Steele, R.S. and Wertz, R.T., Promoting Recovery in Chronic Aphasia with an Interactive Technology, *Archives of PM&R* **78**(8) (1997), 841–46.

[2] Barlow, David and Hersen, Michael, Single-Case Experimental Designs: Strategies for Studying Behavior Change (2nd Ed.), New York, Pergamon Press, 1984.

[3] Brooks, Neil, Closed Head Injury, Oxford, Oxford University Press, 1984.

[4] Chute, Douglas L., Conn, Gretchen, Dipasquale, Madeline C. and Hoag, Melanie, ProsthesisWare: A New Class of Software Supporting the Activities of Daily Living, *Neuropsychology* **2** (1988), 41–57.

[5] Cole, Elliot, Cognitive Prosthetics and AssistiveTechnology, Workshop organized and presented at the Brain Injury Association National Symposium, Philadelphia, November 1–4, 1997.

[6] Cole, Elliot, New Treatment Methods for Executive Dysfunction, panel presentation at the Brain Injury Association National Symposium, Philadelphia, November 1–4, 1997.

[7] Cole, Elliot, Dehdashti, Parto and Yonker, Valerie, Treatment of Plateaued Traumatic Brain Injury Patients by Using Computer-based Cognitive Prosthetics: A Field Study, NIH Neural Prosthesis Workshop, October 15–17, 1997.

[8] Cole, Elliot, Computer-Based Cognitive Prosthetics for the Treatment of Acquired Cognitive Disorders, Second World Congress on Brain Injury, Seville, Spain, May 9–14, 1997.

[9] Cole, Elliot, Matthews Jr., Michael K., Petti, Linda and DeStefano, Mary, Tutorial on Computer-Based Cognitive Prosthetics, organized and presented at the Brain Injury Association National Symposium, Dallas, November 1996.

[10] Cole, Elliot, DeStefano, Mary, and Petti, Linda, Cost Effective Treatment of Brain Injury, presentation at the Medical Case Management Conference, Orlando, September 1996.

[11] Cole, Elliot, Dehdashti, Parto, Matthews Jr., Michael K. and Petti, Linda, Rapid Functional Improvement and Generalization in a Young Stroke Patient following Computer-Based Cognitive Prosthetic Intervention, Presentation at *NIH Neural Prosthesis Workshop*, Bethesda, Maryland, October 19–21, 1994.

[12] Cole, Elliot, Dehdashti, Parto, Petti, Linda, Angert, Marlene, Design and Outcomes of Computer-Based Cognitive Prosthetics for Brain Injury: A Field Study of 3 Subjects, *Neurorehabilitation* **4**(3) (July 1994).

[13] Cole, Elliot, Dehdashti, Parto, Petti, Linda, Angert, Marlene and Dray, Susan, Participatory Design with Cognitively Impaired Users: The Insight of Brain Injury Patients Designing Their Prosthetic Software, paper presented at the International Symposium on Human Factors in Organizational Design and Management, Stockholm, Sweden, May 31, 1994.

[14] Cole, Elliot, Dehdashti, Parto, Petti, Linda and Angert, Marlene, Participatory Design for Sensitive Interface Parameters: Contributions of Traumatic Brain Injury Patients to Their Prosthetic Software, CHI '94, *ACM Conference on Human Factors in Computing Systems, Poster Sessions*, Boston, Massachusetts, April 26 and 27, 1994.

[15] Cole, Elliot, Petti, Linda, Matthews, Jr., Michael K. and Dehdashti, Parto, Participatory Design in Computer-Based Cognitive Prosthetics, Presentation at NIH Neural Prosthesis Workshop, October 13–15, 1993.

[16] Cole, Elliot, Dehdashti, Parto, Petti, Linda, Implementing Complex Compensatory Strategies for Brain Injury, presentation to the American Congress of Rehabilitation Medicine 70th Annual Meeting, Denver, Colorado, June 25–27, 1993; abstract published in *Archives of Physical Medicine and Rehabilitation* **74**(6) (June 1993), 672.

[17] Cole, Elliot, Dehdashti, Parto, Petti, Linda and Angert, Marlene, Computer Software as a Cognitive Orthotic, presented at NIH Workshop on Neural Prosthetics, Bethesda, Maryland, Oct 13–15, 1992.

[18] Cole, Elliot and Dehdashti, Parto, Interface Design as a Prosthesis for Individuals with Brain Injuries, *SIG/CHI Bulletin* **22**(1) (July, 1990), 28–32.

[19] Cole, Elliot and Dehdashti, Parto, Increasing Personal Productivity of Adults with Brain Injury Through Interface Design, Presentation at ACM SIG/CHI 88, Washington, D.C., May 1988, (abstract Only) *SIG/CHI Bulletin*, October, 1988.

[20] Cole, Elliot and Bergman, Marilyn, Application of Theory and Methods from Computer Science to the Use of Microcomputers for Community Re-Entry of Closed Head Trauma Clients, (Abstract Only) *Cognitive Rehabilitation* **5**(4), (July/August

1987), 29, presentation at Cognitive Rehabilitation Conference, Medical College of Virginia, September 1987.
[21] Dowds, Murdo M., Personal Communication, May, 1997.
[22] Dowds, Murdo M. and Robinson, Kelly, Assistive Technology for Memory Impairment: Palmtop Computers and TBI, Braintree Hospital Traumatic Brain Injury Neurorehabilitation Conference, Cambridge, Massachusetts, September 28, 1996.
[23] Englebart, Douglas C., A Conceptual Framework for the Augmentation of Man's Intellect, *Vistas in Information Handling*, Howerton and Weeds, eds., Washington, DC, Spartan Books, 1963, pp. 1–13.
[24] Freund, Hans-Joachim, Sabel Bernard A. and Whitte, Otto W. eds., *Advances in Neurology Vol. 73: Brain Plasticity*, Philadelphia, Lippincott-Raven, 1997.
[25] Friedman, Mark and Cole, Elliot, Opportunities for AI in the use of Computer-Based Cognitive Prosthetics, AAAI Fall Workshop on AI for Disabilities, AAAI Press, November 19–23, 1996.
[26] Goodenough-Trepagnier, Cheryl, Visual Analogue Communication: An Avenue of Investigation and Rehabilitation of Severe Aphasia, *Aphasiology* **9**(4) (1995), 321–341.
[27] Henry, Kimberly, Personal Communication, November 15, 1989.
[28] Henry, Kimberly, Friedman, Mark, Szekeres, Shirley and Stemmler, Debra, Clinical Evaluation of Prototype Portable Electronic Memory Aid, *Proceedings of the RESNA 12th Annual Conference*, RESNA '89, June 1989, pp. 254–255.
[29] Hersh, Neil A. and Treadgold, Lawrence G., NeuroPage: the Rehabilitation of Memory Dysfunction by Prosthetic Memory and Cueing, *NeuroRehabilitation* **4**(3) (1994), 187–197.
[30] Hoepfer, Maurene, Computers Help Reprogram Injured Brains, *Pennsylvania Medicine* (April 1996), 34–36.
[31] Keen, Peter G.W. and Scott-Morton, Michael S., *Decision Support Systems: An Organizational Perspective*, Reading, MA, Addison Wesley, 1979.
[32] Kirsch, N.L., Levine, S.P., Lajiness, R., Mossaro, M., Schneider, M. and Donders, J., Improving Functional Performance with Computerized Task Guidance Systems, *Proceedings Compte Rendu International Conference of the Association for the Advancement of Rehabilitation Technology* ICAART 889, June 1988, pp. 564–56.
[33] Kirsch, Ned L., Levine, Simon, P., Fallon-Krueger, Maureen and Jaros, Lincoln A., The Microcomputer as an 'Orthotic' Device for Patients with Cognitive Deficits, *Journal of Head Trauma Rehabilitation* **2**(4) (1987), 77–86.
[34] Levinson, Richard, The Planning and Execution Assistant and Trainer (PEAT), *Journal of Head Trauma Rehabilitation* **12**(2) (1997), 85–91.
[35] Matthews, Jr., Michael K. and Cole, Elliot, Comparison of Independence Training, Presentation at American Neuropsychiatric Association Annual Conference, Abstract published in *J Neuropsychiatry* **9**(1) (1997), 155.
[36] Merzenich, Michael M., Jenkins, William M., Johnston, Paul, Schreiner, Christoph, Miller, Steven L. and Tallal, Paula, Temporal Processing Deficits of Language-Learning Impaired Children Ameliorated by Training, *Science* **271** (January 5, 1996), 77–81.
[37] Nudo, R.J., Milliken, G.W., Jenkins, W.M. and Merzenich, M.M., Use-dependent Alterations of Movement Representations in Primary Motor Cortex of Adult Squirrel Monkeys, *Journal of Neuroscience* **16**(2) (January 15, 1996), 785–807.
[38] Parente, Rick, Personal Communication, April 11, 1991.
[39] Scientific Learning Corporation, See www.scilearn.com.
[40] Steele, Richard D., Weinrich, Michael, Carlson, Gloria S., Recipe Preparation By a Severely impaired Aphasic Using the C-VIC 2.0 Interface, *Proceedings of the RESNA 12th Annual Conference*, RESNA '89, June 1989, pp. 218–219.
[41] Stein, Donald G., Brailowsky, Simon and Bruno, Will, Brain Repair, New York, Oxford University Press, 1995.
[42] Tallal, Paula, Miller, Steve, Bedi, Gail, Byma, Gary, Wang, Xiaoqin, Nagarajan, Srikantan, Schreiner, Christoph, Jenkins, William and Merzenich, Michael, Language Comprehension in Language-Learning Impaired Children Improved Acoustically modified Speech, *Science* **271** (January, 5, 1996), 81–84.
[43] Tallal, P., Miller, S.L., Bedi, G., Byma, G. Jenkins, W.M., Wang, X., Nagarajan, S.S. and Merzenicn, M.M., Training with Temporally Modified Speech Results in Dramatic improvements in Speech Perception and Language comprehension, *Soc. Neuro. Abstr.* **21**(Part I) (1995), 421.
[44] Wilson, Barbara A, Evans, Jonathan J., Emslie, Hazel and Malinek, Vlastimil, Evaluation of NeuroPage: A New Memory Aid, in press.