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Cognitive Prostheses:

Communication, Rehabilitation and Beyond

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Abstract: The concept of cognitive prosthesis, a system developed to support and augment the cognitive abilities of its user, is discussed, particularly in the context of users who have some form of cognitive loss or impairment. Relevant research issues are highlighted and research systems described, particularly in the field of Augmentative and Alternative Communication (AAC) for people with impaired communication.

Keywords: Cognitive prosthesis, cognitive impairment, cognitive support, assistive technology, assistive systems, augmentative and alternative communication, AAC, alternative man-machine interaction, human-machine systems.

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INTRODUCTION

There are many ways in which computer-based assistive systems can help people with disabilities to live more fulfilling and satisfying lives [2]. Some of the most useful systems are those which augment or replace physical deficits experienced by the user, for example speech output devices can provide non-speaking individuals with synthetic or stored speech, and word-processors can assist people with physical disabilities to type text.

Cognitive deficits, as with physical disabilities, are congenital (from birth) or acquired (due to accidents and injuries later in life). Congenital disabilities, such as cerebral palsy and Down's syndrome, may result in varying degrees of learning disability, while acquired disabilities, following events such as cerebro-vascular accident (CVA) or traumatic brain injury (TBI), often result in the loss of cognitive ability, including faculties of language and memory.

Systems which support people with physical deficits can be regarded as physical prostheses, whereas systems that support or augment the abilities of people who suffer cognitive deficits can be seen as cognitive prostheses.

Overview of Cognitive Prostheses

Computer-based cognitive prostheses have been found to be beneficial with users who have suffered traumatic brain injury (TBI) [10-15], assisting them to perform essential tasks and in some cases to return to fulfilling employment. Cognitive prostheses developed for clients with TBI [10-15] have shown that a significant increase in level of function can be achieved by users resulting from their use of the systems, and evidence of a generalised increase in neuro-cognitive functioning in clients has been seen. The systems are highly customised to the individual needs of the users, with their human-computer interfaces and functional attributes tailored to the particular cognitive deficits. This approach is reported to have been effective in returning certain individual clients to productive occupations. An important key to this is that the prosthetic systems are highly customised to the functional needs of the individual user, with significant attention to detail in the customisation. Word-processing software, schedulers and other computer-based productivity tools have been developed for individual users, the functions of these tools being focused closely on the specific deficits of each user.

Systems such as personal organisers and schedulers are being used to try to improve the performance in practical and daily living tasks of users with various cognitive disabilities [17,19,20,35]. A system developed to remind a client with short-term memory deficiency to perform daily living tasks reduced significantly the requirement that that client had for personal reminding from care-givers [17]. Subjects with cognitive disabilities have been found to work more productively when using a computer-based aid to monitor and guide them in vocational workshop tasks [19]. A personal organiser has also shown promise for improving the punctuality of task performance for students with learning or attention deficit disorders [35], and automatic cues have been seen to help a patient with dementia to perform hand-washing tasks with less help from a care-giver [20].

Vanderheiden and Cress [30] proposed the concept of the "companion" system, a system that would assist people with cognitive impairments. The relationship between the user and the system would be seen as an intellectual partnership, with the system performing tasks such as reminding, monitoring, problem-solving and crisis resolution. It would also do location finding and communications (for emergency alarms). These functions would all contribute to increasing the personal independence of the user. The ethical issue of "who is in charge" is raised here; it is essential that the system behave as assistant and advisor (hence "companion") for the cognitively impaired user, rather than as director. These issues have also been highlighted in the context of augmentative and alternative Communication (AAC) [1], where the system is typically seen as a "slave" to the user (who is "master"). The concept of "team" or "partnership" is also relevant here, in that the user and system can be seen as collaborating towards a mutual goal which is of ultimate benefit to the user. In the case of cognitive impairment, however, the cognitive prosthesis may have to be somewhat more proactive relative to its user. It may need to prompt and advise its user, and in emergency situations be assertive to a degree and capable of raising alarms, but it should not typically be seen as controlling every aspect of the user's life. There are subtle but important issues here that require further consideration and research.

Augmentative and Alternative Communication

The field of augmentative and alternative communication (AAC) [4,6,22,32,33] involves assisting people with impaired communication to communicate, using technology where appropriate to help overcome communication difficulties. Most AAC systems tend to support or augment their user's limited ability to produce speech. Some AAC access techniques, such as semantic compaction [5] and dynamic iconic displays [28], provide access to spoken language using picture coding as an alternative to literacy-based access. Although some users attain high levels of efficiency and automaticity, new user skills have to be developed, and the level of success with the access technique is dependent on the user's memory abilities and motivation.

Techniques such as these can be viewed mainly as tools to help overcome physical limitations in the users. They involve varying degrees of cognitive load during learning and use, but they can reduce the physical effort and difficulty involved in encoding text into an AAC system or word-processor. In most cases they are a user's only physical means of writing text or communicating with other people.

Prediction techniques can assist AAC users to enter text during written communication. Users with existing literacy skills do not need to learn a new coding system in order to make use of prediction, but there is a degree of cognitive load on the user during use. The user has to scan a prediction menu of characters, words or phrases in order to select an item, which involves cognitive effort.

A system which simply enables a non-speaking person to type messages to another person might be helping the user to communicate by overcoming some of his or her physical limitations, but it does not offer any extra cognitive support to the user. Some AAC systems are used to support the cognitive (language or memory) needs of people who are non-speaking through congenital or acquired communication disabilities, such as cerebral palsy or aphasia following brain damage [26]. A principal aim in AAC research is to develop computer-based systems which perform as much of the communication task as technically possible, leaving the user to concentrate his or her efforts on making choices from the options which the system can offer them. These systems use techniques such as word prediction, natural language processing, modelling of conversation structure and content, fuzzy information retrieval of conversational text, semantic networks and scripts, some of which techniques can now be found in commercial AAC systems [16,18,32,34].

Summary

Cognitive prostheses have been developed for a number of roles in rehabilitation and communication, including helping people to make a (partial) return to professional life and increasing their personal independence, and improving their ability to communicate with other people. Beyond this, they contribute to the personal development of people (including those without disabilities) in a more open-ended way and can improve their performance, and confidence, in a number of activities. Examples range from mathematical calculators to spelling and grammar checkers that can augment the abilities of people and effectively expand or improve the things that they can do.

Although AAC systems have the potential to act as cognitive prostheses [3], most current systems function principally as physical prostheses. AAC systems have potential for much more, however, and there are a number of research issues to be considered if AAC systems are to replace or augment a range of cognitive faculties (such as language processing in persons with non-fluent aphasia) for their users.

RESEARCH ISSUES

Computer-based cognitive prostheses clearly have a large contribution to make to the well-being of many people with cognitive deficits and impairments, including those with acquired and congenital conditions. There are also many ways in which they might augment or extend the cognitive faculties of non-disabled people. There is an opportunity to establish a strategic view of possibilities, in order to map relevant research areas and the opportunities that they afford. The key aspects are how cognitive activity can be modelled in computer-based systems and how such models can be interfaced to users. Research questions to be addressed include:

- what areas of cognitive activity are amenable to computer modelling ?
- what computing techniques can be used to create these models ?
- what user interfaces will be required for the variety of cognitive difficulties which users will present ?
- where should the locus of control lie between the user and the system if the system is to offer an optimal level of help to the user ?
- how can systems be tailored efficiently, and in fine detail, to the needs and existing cognitive abilities of the user ?

Computer Modelling of Cognitive Activity

As knowledge of human cognition and the power and memory size of computer systems advance, it will become possible to build models of cognition and interaction, and use them to simulate more of the user's cognitive activity in machine form. Certain aspects of the non-conscious processing associated with human language and communication can be simulated in computer-based AAC systems, for example. Phatic phrases can be produced in a semi-automatic manner to help maintain the flow of a conversation, and script-based systems can help model transactional communication. Fuzzy information retrieval can assist in simulating the topic shift which occurs in normal conversation, and semantic networks can assist with sentence prediction and story telling. Such techniques are valuable in an AAC context, where the aim is to assist AAC users to participate in conversation and achieve goals in their communication with other people.

Computing Techniques

The fields of Computer Science and Artificial Intelligence have generated a large number of computational techniques which relate, to differing extents, to aspects of cognitive activity. Many of these can perform useful tasks within the context of helping people with disabilities. Examples include natural language processing (word prediction and text production in AAC, speech recognition), robotics (lifting and moving things for people with physical disabilities), neural networks (speech and gesture recognition), and semantic networks (in AAC systems). Further development and refinement of these techniques, and the development of new ones, will give progressive improvement in the level of support that prosthetic systems can offer to human users.

User Interfaces

The variety of cognitive difficulties that users may present are wide-ranging. The types of user interface which will be needed could therefore also range widely. People with aphasia (e.g. after CVA) may be unable to use traditional language-based interfaces, and need to use a limited user-defined vocabulary augmented by personalised graphics and symbols. A "companion" system may have to advise or guide its user by video or graphical means.

Many interface methods place a cognitive load on the user. A typical approach is to bypass an impairment in the user or augment the user's existing abilities by using alternative channels for information flow, so incurring or increasing a load on other faculties in order to gain advantage over the impairment. Interface methods are useful if they give benefits which outweigh the cost of using them. In the case of users with cognitive impairments, the interface will use residual cognitive faculties which the user can employ to compensate for missing or impaired ones. There is much scope for the development of new interface methods which will open new channels of communication for people with cognitive impairments without imposing any additional cognitive load.

Locus of Control

The locus of control is of great importance, and this issue requires further debate and consideration in order to map out how much control a cognitive prosthesis should have over the user when the user requires a lot of advice and assistance from it. While it may seem undesirable for the user to have to rigorously follow instructions from a computer-based system (as can be the situation after CVA, for example), it may be that this gives the user more independence from human care-givers, and therefore improves the user's self-esteem and quality of life. The trade-off between independence from other humans and independence from the machine raises some rather subtle issues; users may well be content to cede a lot of control over their behaviour to a machine for significant periods of time if it means that they retain more personal independence from other people in their life. A machine which is accepted as a friend or advisor may be tolerated, and even liked, in the role of "master", if it delivers significant benefits in that role. In the case of the AAC system, however, which has the task of helping its user to talk to people, control must reside with the user to determine what the system proposes to say on their behalf. One would therefore expect a typical AAC system to function as a "slave" under the explicit command of its user [1]. A system operating as an assistant or advisor (the "companion" model [30]) may be allowed to range from "slave" to "master", however, depending on user circumstances and requirements. Work with automatic reminding systems [17], for example, has shown how heavy reliance on the reminding system can reward the user with greater independence from care-givers.

Tailoring of Systems to User Requirements

The work on cognitive prostheses for clients with TBI [10-15] has shown the importance of being able to tailor the system and its user interface closely to the needs of the individual user in order to achieve an effective outcome. Such a design process must be lengthy and costly, and it would be advantageous to automate at least part of it. User needs can change with time, particularly if use of the prosthesis is having a therapeutic effect, hence an adaptive system which can change automatically to track changes in user performance and behaviour would be valuable. An important priority is therefore to identify how technology can assist with analysing the residual cognitive faculties of an individual user, modelling a prosthesis to augment these faculties, and monitoring the use of the prosthesis in order to adapt it to the changing needs of the user. It is unlikely that this process can be performed completely automatically, hence a key issue is to identify what human involvement is necessary in the design and adaptation of the prosthesis, and how this involvement can be efficiently achieved. Some monitoring of the prosthesis as it adapts to its user may also be required, in order to ensure that the system is tracking changes in the user and modifying its behaviour in an optimal fashion.

Other Possibilities for Cognitive Augmentation

Some other examples of possible cognitive augmentation are memory processes (multi-media scrapbooks could assist those with memory problems to reminisce about past events), planning, creative thinking (using computer art systems) and expression of emotion. The cognitive prosthesis can provide a "scaffold" around which the user can re-build a set of skills, knowledge and abilities, re-affirming memories (e.g. in a multimedia reminiscence scrapbook) and helping the user to recognise their sense of identity. Human emotion can be simulated in synthetic speech [21]. Affective computing [24] and Kansei processing [9,23,29] are of growing importance in human-computer systems. This raises the possibility of an AAC system sensing the emotional states of the user and/or communication partners, and adapting the assistance which it gives to the user accordingly, for example by predicting phrases of appropriate emotional tone for a particular interaction, selecting some jokes if humour is anticipated [25], or planning conversational strategies to defuse a potential argument. A "companion" system may be able to monitor the emotional state of its user, and advise the user to adopt a particular behaviour (e.g. perform a calming activity) or raise an alarm in response to the change in emotion.

EXAMPLES OF RESEARCH SYSTEMS

The authors are involved in the development of AAC systems which give cognitive support to their users by anticipating what is likely to be required next in an interaction and prompting the user accordingly. A small number of appropriate messages (phrases and/or stories) are presented to the user by the system; the user can then confirm the selection of one such message in order for it to be output to conversation partner(s). This assists the user in finding and selecting appropriate things to say, although the user needs to be able to recognise and understand appropriate things to say when prompted with them. Examples of such systems are ScripTalker™, TalksBac and Talk:About™.

ScripTalker™

ScripTalker [16,18] is an AAC System which is designed to assist a user to conduct transactional conversations, i.e. to attain goals such as buying items in shops, consulting a doctor about health issues, or ordering a meal in a restaurant. It is script-based [27], and assists its user to navigate through conventional interactions, such as those that occur in shops and restaurants, by prompting the user with appropriate messages in an appropriate sequence for use in conversation. The system contains a script-based model of a number of conventional interactions, and can assist the user to be proactive and responsive in transactions in a manner that would not normally be possible for a non-speaking person. The computer-based modelling of transactional sequences therefore augments the ability of the non-speaking user to communicate with other people by simulating some of the cognitive activity (the planning and sequencing of statements and responses) which is required during conversation, and using that to enable the AAC system to prompt the user with appropriate messages. The user only has to confirm a prompted message for the system to output it in synthetic speech. For a non-speaking person, such assistance in communication can make the difference between interaction and isolation. The system is sufficiently flexible to let the user vary the sequence of spoken items and compose original phrases, so it does not constrain a user who requires flexibility in a conversational situation.

TalksBac

A cognitive prosthesis must support or augment cognitive processes which would normally occur within the user, and deliver some benefit to the user in the form of anticipation of future needs or (partial) automation of processes which the user needs to engage in. One example was the TalksBack system [7,8] which used a semantic network to help aphasic people find and use text items that they were seeking but could not recall because of their brain damage. As such, TalksBack was augmenting the residual cognitive faculties of the user, and performing functions for them which they no longer could. Systems which assist with the retrieval of messages by using (for example) knowledge about messages which have been used previously or knowledge about the prevailing topic of discussion can be seen as augmenting the cognitive processing which occurs within the user.

TalksBac is an AAC system, derived from the earlier TalksBack, that exploits the residual ability of some non-fluent aphasic people to recognise familiar words and short sentences [31]. People with aphasia find AAC systems difficult to use as they require either good literacy skills or knowledge of an alternative symbol-based system in order to use them. People with aphasia also have problems in retrieving words. The user is not required to learn an alternative coding system in order to use TalksBac, nor is he or she required to have intact literacy skills. The system instead meets the user at his or her literacy level and assists in the retrieval of pre-stored personal sentences and stories by offering the user probable items based on previous system use. The system adapts automatically to reflect the usage over time of the individual user. Case studies have shown that the system acts as a therapeutic tool for spoken language for some users.

Talk:About™

Talk:About™ is a story-based communication system that allows users to create, retrieve, modify and narrate stories within interactive communication [34]. A two-year study investigated the use of this system with six young people, and showed that the development of story-writing and story-telling skills had a positive effect on the interactive communication of young people with unintelligible speech. Evaluations indicate that subjects were able to initiate and control communication more effectively with the system. Their self-esteem and willingness to interact improved, as did their formal writing skills. Most notably, the communication system had a therapeutic effect with subjects who had oral speech with poor intelligibility.

The project highlights the importance of providing a vehicle through which AAC users can develop natural communication skills. For example, a non-speaking eleven year-old child was able to initiate and narrate jokes on her own accord using a predictive word-processor. Despite limited literacy skills, users are able to access new vocabulary on their own using spoken feedback. It is thus possible for users to do things independently and develop through the language/literacy process. The user is able to achieve success using the skills they have; the system does not hinder development, rather it allows the user to experiment and develop at their own pace. One of the authors is now investigating further ways to provide the scaffolding necessary to encourage self-experimentation.

Summary

The systems described above all augment parts of the cognitive tasks involved in communication. They illustrate how technology can be harnessed to reduce the cognitive effort involved in retrieving and expressing communicative information. The use of predictive and adaptive technology can assist in the cognitive as well as the physical process of communication interaction.

CONCLUSION

Computer-based systems can impose new and artificial access methods on the user, compared to using residual and natural faculties within the user, and new skills have to be learnt in using the system and its interface. There is therefore a training cost involved in learning these new skills, but such skills are very useful once learnt. They give the user access to possibilities which he or she previously did not have, and expand the potential for personal achievement and growth. Learning of new skills, and use of a cognitive prosthesis, can have motivating and therapeutic effects in themselves, and users can be seen to experience personal development as a result.

Greater benefit may lie, however, in developing systems that reduce further the cognitive load required to use AAC systems. The benefits to the user include: reducing the amount of physical effort involved in typing or retrieving (from computer storage) messages or stories; helping the user to improve spelling or word usage; receiving suggestions from the system of appropriate things to say (where the user has had some cognitive loss which affects communicative competence). There may well be a trade-off occurring in which the user invests cognitive effort in one way in order to attain advantage in another. As future systems evolve and advance there will be increased opportunity to augment or substitute the cognitive activity in the user with computer-based processing. All forms of cognitive impairment could benefit from this, including users with acquired and congenital impairments.

Cognitive prostheses can augment human abilities and extend the range of capabilities of their users. They are particularly useful for people with disabilities, where computer-based prostheses can assist users to perform tasks that disability otherwise denies. The development of new computing techniques and modelling methods will enable more powerful systems to be developed, bringing ever more improvement to the lives of people with impaired communication and other disabilities.

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