NeuroRehabilitation 28 (2011) 271–280
DOI 10.3233/NRE-2011-0655
IOS Press

The future of intelligent assistive technologies for cognition: Devices under development to support independent living and aging-with-choice

Jennifer Boger[a,b] and Alex Mihailidis[a,b,*]
[a]*University of Toronto, Toronto, ON, Canada*
[b]*Toronto Rehabilitation Institute, Toronto, ON, Canada*

Abstract. A person's ability to be independent is dependent on his or her overall health, mobility, and ability to complete activities of daily living. Intelligent assistive technologies (IATs) are devices that incorporate context into their decision-making process, which enables them to provide customised and dynamic assistance in an appropriate manner. IATs have tremendous potential to support people with cognitive impairments as they can be used to support many facets of well-being; from augmenting memory and decision making tasks to providing autonomous and early detection of possible changes in health. This paper presents IATs that are currently in development in the research community to support tasks that can be impacted by compromised cognition. While they are not yet ready for the general public, these devices showcase the capabilities of technologies one can expect to see in the consumer marketplace in the near future.

Keywords: Intelligent assistive technology (IAT), cognition support, smart homes, independent living, aging with choice

1. Background/introduction

Assistive technologies are devices, tools, and/or systems that are used by people of all abilities to accomplish tasks they would be otherwise unable to do. For people with disabilities, assistive technologies can augment a person's abilities to enable safe, independent, and inclusive participation in daily life. The term "assistive technology" encompasses a wide range of devices and tools, ranging from simple (such as canes, grab-bars, and wall calendars) to complex (such as electronic wheelchairs, computerised task support, and remote health monitoring) [1]. Technologies designed to include or support people with disabilities need to reflect the nature of the intended users' capabilities, which are often highly diverse and may change considerably over both the short- and long-term.

Significant advances in computer hardware and software have made it possible and realistic for assistive technologies to incorporate artificial intelligence (AI) to support decision making tasks. Broadly, the term AI implies using a computer to interpret situations and take actions that are most likely to achieve the best expected outcomes given the information that is available [2]. Put another way, intelligent (computer) agents are able to make rational decisions about the best course of action to take, based on what the agent knows about the state of world (i.e., context). The ability to take context into account when making decisions and the ability to make reasonable decisions regarding situations an agent may not have seen before are two fundamental differences between *intelligent* versus *smart* technologies, which simply react to predefined situations in a predetermined manner. For example, a smart technology could turn on the lights whenever someone was in

*Corresponding author: Alex Mihailidis, 160 – 500 University Ave., Toronto, ON, Canada, M5G 1V7, Canada. Tel.: +1 416 946 8565; Fax: +1 416 946 8570; E-mail: alex.mihailidis@utoronto.ca.

ISSN 1053-8135/11/$27.50

a room while an intelligent technology could also dim the lights if the person started watching a movie, but not while they were watching the news. One example of the effectiveness of context aware technology is the medication reminder system developed by Hayes et al. [3]. Using a few environmental sensors and simple rules, such as "Don't prompt if participant is on the phone. Wait until they are off the phone to prompt," the system was able to use what it knew about its environment to wait until the user was not otherwise engaged before prompting him/her to take his/her medication (and only if she/he had not done so already). In trials with ten older adults (> 65 years of age), participants achieved an average of 92% medication adherence when the device was used, compared to 74% with time-based prompting (e.g., a reminder was given at the same times each day, regardless of context) and 68% when no prompting device was used [3].

This medication reminder device is an example of an intelligent assistive technology (IAT). IATs are a specific branch of assistive technology that employs AI to achieve semi- or fully-autonomous decision making capabilities. IATs have great potential, particularly for supporting people with cognitive disabilities, because of the ever-increasing ability of these devices to provide appropriate support that can adjust to fit specific needs with little or no effort on the part of the technology users (i.e., the person with the disability, family members, professional care team, etc.). Importantly, IATs are able to provide support only when it is needed and are able to adapt to changes in the users' needs and preferences over time, which are key elements to ensuring that people using an IAT are appropriately supported yet as independent and actively engaged as possible. This, in turn, creates tremendous potential for IATs to enable people with disabilities to make more choices about where and how they wish to live.

This paper presents examples of IATs to support cognition that are currently under development in the research community. While IATs are usually developed to address the needs of a specific user group, one can imagine how most devices discussed here could be altered to support the needs of other groups, including the general public. Importantly, the devices presented below represent IATs where the developers have considered the cognitive and physical abilities of potential users and designed the interface to be appropriate and usable by the target population, which includes a caregiver as well as the person with a disability. Examples include devices that require no explicit feedback from the user as well as devices that have greatly simplified interfaces so that they can be initialised by someone with little time or technological experience. This paper also touches on challenges in IAT development, including the capture and interpretation of data in a way that is meaningful to stakeholders, including other autonomous IATs. It is important to keep in mind that regardless of their potential, IATs are not intended to replace a human caregiver. Rather they are designed to assume some of the tasks that are usually performed by a caregiver, thereby supporting the caregiver as much as the care recipient. While the devices discussed in this paper are not yet ready for consumers, it is hoped that they will provide illustrations of IATs' tremendous potential to support cognition and provide a snapshot of the types of technologies we can expect see emerging in the marketplace over the next decade or so.

2. Autonomous detection of changes in health and well-being

Health (or the lack thereof) affects virtually every aspect of life. Maintaining good health can be challenging, particularly for people with long-term or multiple morbidities (e.g., [4,5]). Difficulties in monitoring and managing health care are exacerbated for someone with a cognitive disability as they are more likely to have multiple morbidities and rely heavily, or even completely, on their circle of support to detect changes in health [4]. The ability of the clinical community (including emergency response services), family members, and the people with the morbidities themselves to effectively manage conditions is highly dependent on having an accurate, dynamic, and holistic understanding of an individual's health. Understanding long-term health patterns, as well as early and quick detection of changes in these patterns, enables more effective interventions and promotes a preventative (rather than reactionary) approach to supporting well-being. From a clinical perspective, information regarding one's well-being is typically a collection of sporadic observations made by medical practitioners, the care recipient's family, and the individual themselves. While this approach yields valuable information, it often results in missed or misrepresented data as records consist mostly of unquantified observations (often from memory) by the patient or their families and from discrete and infrequent physiological measurements by clinicians. In a year-long study that followed 445 United States veterans who used a telehealth messaging system to coordinate diabetes treatment at home, participants using the system were found to experience significant decreases in formal care, with an average of 50% fewer hospital visits, 11% less emergency room use, and three fewer days of bed-care [6]. The cost and health benefits from care reductions through the use of a simple, user-driven monitoring system for the management of diabetes alone are impressive; the benefits of employing a more holistic, autonomous approach are enormous.

Employing IATs is one way to significantly improve the representation of a person's health. IATs may not only yield a more accurate representation of one's health through frequent measurements that can be made in one's own home, but could also autonomously detect changes in health, possibly even before the person being monitored notices them.

While there are several systems on the market that allow a user (or his or her caregiver) to measure vitals and share them with a remote clinician (e.g., Philips Telehealth, LifeLink, Corventis NUVANT), in general the data collected undergoes little or no analysis before it is presented to interested parties. The result can be an overwhelming amount of data that is difficult for even a professional clinician interpret, particularly when it comes to long-term trends. A new category of IATs is emerging that are not only able to monitor home activity, but can identify long- and short-term changes in well-being as well. There are a host of providers (e.g., WellAWARE, GrandCare, BeClose, QuietCare, and MedMinder – see [7] for a listing and brief overview of available systems) offering services that are able to monitor health by tracking activity patterns through switches and sensors that have been installed around a home. Through various degrees of autonomy, ranging from completely unguided to manually defined, a model of the occupant's normal routine is generated. These systems are able to detect deviations from the norm, which may indicate an improvement or deterioration in health, and generate a message or, if the situation is deemed to be more critical, warning to the appropriate pre-defined recipients, who can include clinicians, family members, and the individual themselves. With permission from the individual, family members are also able to remotely monitor categorised information and indications of their loved one's health status. While still relatively crude in their detection of events (most employ motion detectors and/or switches), the ability of these devices to provide stakeholders with long-term tracking and preliminary heath analysis represents an invaluable and incredibly powerful tool in proactive and preventative healthcare. Being cognisant of improvements in health may motivate individuals to understand their own health and pursue constructive health habits while early identification of deterioration in heath allows for the early treatment and possible mitigation of health problems. For example, early detection of deviations that may indicate an individual is developing dementia enables the individual and his/her family to seek information and make decisions regarding possible treatment, management, and coping alternatives. As interventions, particularly current drug-based treatments, are usually more successful with earlier implementation, the early detection of dementia could cause a substantial improvement in an individual with dementia's quality of life.

Researchers are investigating novel ways of detecting deviations in health through changes in daily activities. For instance, research indicates that a slower walking speed may be tied to cerebral blood flow and is thought to indicate an increased risk for numerous conditions such as disability, cognitive impairment, institutionalisation, falls, mortality, and complications following surgery [8–10]. Building on this research, Hayes and colleagues have used unobtrusive passive infrared sensors to continuously measure both variability in daily activities and changes in walking speed over extended periods of time [11,12]. In a year-long study of seven older adults with mild cognitive impairment (MCI) and seven healthy aged-matched controls, [13] found that the variability in daily activity was significantly higher in subjects with MCI at most time scales. They have also developed algorithms to measure changes in walking speed [14] and rest-activity patterns [15] over time. It is not difficult to imagine how combining the detection of other factors, (e.g., balance, eating, and toileting), could be used to develop detailed, subtle, and highly-personalised descriptions of an individual's state of health, which would enable automated diagnoses and provide quantifiable rates of change in conditions. This information could then be communicated to clinicians, family, and the individuals themselves at a level and in a manner of that is appropriate for each. The autonomous detection of deviations in health is a rapidly expanding field and includes work by groups such as Skubica et al. [16], Majeed and Brown [17], Park et al. [18], and Suzuki and Murase [19].

While changes in health can be gradual, they can also be acute. Falls are responsible for the greatest number of hospitalisations, are the leading cause of disabilities, and are the third leading cause of death from injuries occurring in Canada and represent the second largest lifetime medical cost in the USA and Australia [20,21].

Many falls occur in the home and can be particularly devastating when they occur on the stairs. The preferred course of action is, naturally, to try and prevent a fall from occurring in the first place. For example, using a handrail while going up or down the stairs is a simple way to greatly reduce the likelihood of a serious fall. Snoek et al. [22] are using computer vision (i.e., a computer analysing incoming images from a video camera(s)) algorithms to identify whether or not the handrail is being used. If a person neglects to use the handrail, verbal or visual reminders could be given, such as the ones found to be effective by Maki et al. [23]. Importantly, the detection method developed by [22] has the potential to recognise context, such as the person carrying a large object, and tailor prompts for safe stair use accordingly. The ability to recognise context means the device could provide specific and pre-emptive prompts, which may be particularly useful to people who have difficulties with planning.

Falls are of particular importance to the older adult population, as they represent the most common cause of accident and injury for this demographic and have associated healthcare costs that are projected to reach $55 billion by 2020 for people over the age of 65 living in the United States alone [24,25]. With current fall detection systems the user wears a bracelet or pendant that he or she triggers through the push of a button when an adverse event occurs. The user is then connected to a live operator via a speakerphone placed in a central room of the home. Difficulties with this approach include accidental triggering of the system, the user being unable to trigger the system (e.g., is not wearing the trigger when an accident occurs, is unconscious, etc.), and hesitation to use the system when it is needed [26,27]. If the user has a cognitive disability, such as dementia, their risk of falling is increased as much as five-fold [24]. Moreover, they are less likely to wear a device and, even if they are, he or she may not remember that they have the trigger or how to use it. Wearable accelerometers address some of these issues (as they do not require a button to be pressed), but still require the user to remember and be compliant with wearing a device. Fall detection embedded in one's environment could circumvent these challenges as it would not require the user to wear anything and would automatically react to a fall without any explicit action from the user. Projects researching this approach include work by [28–30]. While these projects have shown promising progress, detection of the fall is only one half of creating an IAT solution; how to manage the fall is the other. Researchers at the Intelligent Assistive Technology and System Lab (IATSL; University of Toronto/Toronto Rehabilitation Institute) are working on developing HELPER (patent pending), a system that employs computer vision to detect when a fall has occurred and verbally interacts with the user to determine what type of assistance is needed [31–33]. Through a simple question and "yes/no" answer dialogue, the user can make decisions regarding what type of help they would like to receive and who they would prefer the system to contact (e.g., an ambulance, neighbour, or son/daughter). Should the user be unable to respond or should the system be unable to understand the user's answers, a call is automatically placed to a live operator. The system's response to an adverse event can be tailored to reflect the user's decision making capabilities, ranging from fully controlled by the user to the system automatically procuring assistance.

3. Mobility for cognition: Artificial intelligence meets navigation and powered wheelchairs

Mobility is a key component to quality of life as it allows a person to independently move about when and where he or she chooses. Many people with impaired cognition have difficulties with the planning and executing of navigation to a desired destination. As a result, a great proportion of people with cognitive impairments must rely on help from others to get from place to place. Mobility support ranges from assistance with planning routes and navigation from one location to the next (which includes larger-scale, community-based travel and smaller scale movement within a building) as well as the safe use of mobility aids such as walkers and wheelchairs.

The new generation of PDA/cell phones, such as Google's Android and Apple's iPhone, offer potential platforms for wayfinding tecsshnologies because of their portability, GPS capabilities, and touch-screens that allow images to be displayed and easily interacted with. Opportunity Knocks is one of the first examples of a PDA-based navigation device for people who are relatively high functioning but not able to navigate a community setting because of poor short-term memory, such as individuals with mild mental retardation and acquired brain injury (ABI) [34]. Over time, Opportunity Knocks learns about routes and destinations the user frequently goes to. Should the user become lost, he or she can use the device to select a desired destination, which can be displayed as pictures or text. Opportunity Knocks then uses GPS and public transportation routes and schedules (e.g., bus routes) to guide the user to his or her destination. The device will only provide a prompt to the user if he or she is straying from an acceptable route, thereby providing the user with as much independence as possible. Research is underway to improve the device's ability to autonomously learn user preferences, predict where the user is trying to go, and provide tailored guidance the user [35]. Complementary work has been done to develop a combination scheduler, locator, and points of interest map [36]. With this device, a user with ABI can input points of interest (e.g., home, work, etc.), and schedule times and locations of tasks (e.g., 8 AM go to work). The device uses GPS to track the user's current location and can be used as a day planner, as a task alarm, to orient oneself, and to navigate to points of interest (including tasks).

Cognitively impaired people also often have physical difficulties with mobility, which may or may not be related to the cause of their cognitive impairment. Many people with cognitive impairments are too weak, unsteady, or physically incapable of using mechanical aids (e.g., manual wheelchair or a walker). However, to ensure that they and people around them remain safe they are also not permitted to use powered mobility aids, such as an electric wheelchair, unless they are heavily supervised. Through support such as autonomous or assisted navigation and obstacle avoidance, intelligent powered wheelchairs are being developed to complement different cognitive disabilities and enable independent mobility. As a result, intelligent wheelchairs have been estimated to have the potential to provide partial or complete support to 2.6 to 3.9 million (60 to 91 percent) of all wheelchair users in the United States in 2010 alone [37]. As users' abilities vary considerably depending on the person's disability (which in itself will have individually varied traits), an intelligent wheelchair's functions must appropriately complement the intended users' physical and mental abilities. For example, assisted or autonomous navigation could benefit people who have difficulties remembering where they are going, planning how to get there, or recovering from deviations in routes, whereas obstacle avoidance could benefit people with cognitive impairments that cause unsafe driving, such as slow reaction time, impaired attention, compromised decision making capabilities, or aggression.

PALMA is a mobility tool designed to assist children affected by cerebral palsy and is specifically targeted to provide personalised rehabilitation and support to children affected by severe neuromotor problems [38]. An array of ultrasound sensors provides obstacle detection and collision avoidance and the driver is able to control the device through a simple interface, which can be customised to the user and can include buttons, blowing switches, joystick, etc. PALMA can assume different levels of autonomy ranging from fully autonomous to completely user-controlled. Moreover, the controls can be adjusted to match the individual driver's capabilities (e.g., different driving speeds, driving time, minimum time between button pressing, pressing time, scanning intervals) and rehabilitation data can be downloaded to give a detailed report of the driver's progress (e.g., ratio of driving time to operation time, number of stops and simulated crashes, trajectory time, time between commanding actions). In 28 trials with six children (aged three to seven) who had mental retardation ranging from mild to severe, all the participants were able to not only successfully drive using PALMA, but progressed in the amount of navigation they were able to do themselves.

While it is also designed to primarily support users with cerebral palsy, the wheelchair developed by Montesano et al. [39] takes a different approach by having the user provide a short-term, high-level navigation plan that the chair can drive to autonomously. A planar laser mounted at the front of the wheelchair provides a 3D image of the environment to the user via a touch screen. The user then inputs where he or she wishes to go by touching the location on the screen and/or through "go", "stop", "turn left", and "turn right" icons. The wheelchair proceeds to the destination autonomously, avoiding static and dynamic obstacles along the way. In trials with four young-adults who had moderate mental retardation, all the participants were able to safely and successfully navigate a complex route in a school during normal daytime activities, which they would not have been able to do using a conventional powered wheelchair [39].

Researchers are also working to develop mobility for older adults with dementia. The wheelchair being developed by [40] uses computer vision to autonomously detect obstacles and stop the chair if the user does not do so his or herself. The chair provides audio and visual prompts to the user to help him or her navigate around the object. In addition to anti-collision, the wheelchair can use computer vision to autonomously map out an environment. Recent prototype tests had three older adults with mild-to-moderate levels of dementia navigate a randomly ordered obstacle course using six movement tasks (left/right turn, stopping, weaving through obstacles, straight line, and a 180 turn) in both a conventional powered wheelchair and an anti-collision wheelchair. Recently completed pilot trials involving three older adults who had moderate-to-severe dementia (MMSE of 20 or less) resulted in a reduction in collisions of 66 to 80% when the anti-collision used to detect objects directly in front of the chair alone. Research is underway to improve the area of detection. By overlaying the environment's map with labels (e.g., bedroom, dining area, etc.) the user's schedule and preferences can be used to promote participation in daily activities, such reminding the user that an event (e.g., mealtime, favourite television program) is about to occur and providing directions to the event should the driver need them. Research is underway to autonomously estimate the state of the user and generate appropriate responses (e.g., what type of prompts work best with him/her) [41]. Preliminary work is being done to identify objects in a room and use this to automatically recognise the type of room the user is in, even if the person has never visited it before [42].

While the above examples are only a few of the many projects investigating autonomous and semi-autonomous control in wheelchairs, they differ from most because of two main objectives: 1) the expectation and, indeed, encouragement of the user to participate in the task of navigation as much as she or he possibly can, and 2) the ability to operate in both known and unknown environments. These intelligent wheelchairs are designed to improve the ability of the driver to interact with their environment, and by supporting existing abilities and providing compensation only when required, they help to positively impact the driver's motor dexterity, decision-making abilities and feelings of independence.

4. Support for activities of daily living

The ability to complete activities of daily living (ADLs), such as toileting, dressing, and meal preparation, are particularly important as ADLs are fundamental to a person's health, independence and social well-being. Compromised abilities to complete ADL have been shown to be a significant factor in higher rates of depression, loss of control, and a reduced sense of purpose as well as increases in caregiver burden and risk of nursing home placement [43–45]. IATs have the potential to support ADL completion through appropriate compensation of existing cognitive abilities, thus reducing a care recipient's reliance on a caregiver during ADL completion. However, before an IAT can provide support, it must be able to recognise what ADL the user is attempting, if he or she requires assistance, and what kind of assistance is appropriate. The wide range of environmental layouts and conditions makes ADL recognition a difficult problem. In addition, an IAT that assists with ADL completion must be able to recognise different "correct" ways of completing an ADL so that it can follow the user through an activity and avoid erroneous support.

People with ABI commonly have trouble completing ADL as they can omit steps that are required to complete the activity, perform steps in an incorrect sequence, and in some cases, have trouble remembering what activity they are trying to do. Archipel is an IAT that has been designed to provide ADL guidance for people with ABI [46]. Prototyped to support the activity of cooking, Archipel uses an array of sensors, such as switches on cupboard doors and a flow meter on the tap, to detect what objects in a kitchen the user is interacting with. Archipel is able to learn which steps in an activity a user typically has trouble with as well as what type of difficulty they are having: initiation (user has trouble starting an activity), planning (trouble recalling sequencing of steps), attention (trouble staying on task), or memory (trouble remembering where required objects are or what to do next). Based on the type of difficulties the user is experiencing, Archipel attempts to engage the user in the task as much as possible by providing appropriate cues when they are needed, such as lighting up an object of interest (using LEDs) or providing prompts (pictures and/or text) on a touch screen. In a case study with 12 people with mental retardation, Archipel was able to increase the level of independence of even the most capable test subject [47].

COACH is an IAT that is also designed to provide ADL support, but is prototyped to assist older adults with dementia with the activity of handwashing [48, 49]. Instead of a sensor array, COACH employs computer vision using a single overhead camera to track the user's hands and determine what objects he or she is interacting with. If the user appears to be having difficulty, such as missing or repeating a step, COACH is able to provide him or her with an audio or audiovisual cue over a monitor mounted above the sink. COACH is able to autonomously learn about a user's preferences, estimate the user's abilities, and detect short- and long-term changes in these abilities. This understanding of the user enables COACH to tailor its guidance of the activity to the individual and changing needs of each user. COACH has shown promise in pilot trials with older adults with dementia, reducing and sometimes even eliminating the need for caregiver support [49–

51]. Researchers are advancing COACH's capabilities through the addition of the activity of tooth-brushing and the modification of COACH for use with children who have autism spectrum disorders. A key difference in the application of COACH as a guide for children with autism is that it is designed to function as a more interactive teaching tool rather than a reminder device, as is the case for older adults with dementia. Prototype testing has just begun and the device appears to be accepted and usable by a child with autism [52].

A person's well-being is not only dictated by his or her physiological state. Having fun, participating in meaningful occupations (such as a hobby), being actively involved in one's environment, and interacting with other people are all vital for a healthy state of mind [53]. Individuals with dementia often have difficulties interacting with others in a meaningful way because of related impairments, such as compromised memory and communication skills. These impairments are thought to cause or exacerbate many of the negative quality of life changes associated with dementia such as low self-esteem, compromised social networks, and depression [54]. Having regular access to the creation of art has been shown to cause positive changes in mood and cognition for people with dementia and provide them with a form of expression that can enable meaningful connections to others [54,55]. ePad is a device being developed by Hoey et al. [56] to be used by older adults with dementia during sessions with an arts therapist. The user is presented with simple creative arts tasks, such as painting or creating a collage, on a large touch screen. The system estimates the user's engagement in the task by tracking his or her interactions with the touch screen and by using computer vision to track where he or she is looking. Based on the user's level of engagement and preferences, which are autonomously learned and adjusted over time, ePad can take actions to maintain or encourage engagement, such as giving audio and/or visual prompts. Therapists can use ePad not only to support specific art therapy strategies, but also as a new way to perform objective assessments, such as monitoring changes in a client's level of engagement over time.

Communication and interacting with the environment presents a great challenge for people who are locked-in. A consortium from the European Union is working together on creating Brain-Computer Interfaces with Rapid Automated Interfaces for Nonexperts (BRAIN) [57]. The goal of the BRAIN project is to develop signal acquisition, operations protocols, signal translation, and interfaces and applications that will be used to build device that will provide a range of disabled users who have limited or no capacity to interact with people and the environment around them with a way to do so. A focus of the project is to have affordable and non-invasive hardware perform the autonomous detection, acquisition, and implementation of the most appropriate brain-computer interface for each user. The result would be that non-technical people, such as the user's family, will be able to assist their loved one in using their BRAIN device. Possible applications of a BRAIN device include control of assistive devices, home environments, communication, and entertainment. Scheduled to be completed in late 2011, the BRAIN project is well underway and has resulted in publications such as [58–60]. Work by has been done by other researchers to try and provide access to locked-in people through methods such as computer vision detection of changes in facial features, infra-red tracking, oculography (gaze-based systems), and voluntary and involuntary electrodermal activity [61,62]. Research involving communication with locked-in people provides interesting new possibilities of ways for people with cognitive impairments to interact with their environments, as it will surpass many of the communication modalities people with cognitive disabilities often have trouble with.

5. Future directions and implications

With the rapid growth in computing hardware and software capabilities, applications of IATs are becoming limited only by our imaginations. While the possibilities of IATs for supporting cognition are exciting, it must be remembered that the high levels of user dependence and consequences of device failure demand appropriately high levels of IAT reliability and accuracy; one missed fall or a wrong interpretation of health trends could have significant and tragic consequences. Moreover, the considerable variability in the abilities of intended users, even for people within the same cognitive impairment and demographic, results in an extremely diverse user group. Hence while these types of IAT may offer significant benefits, it also remains an extremely challenging design paradigm. IATs must be appropriate, dynamic, accurate, and robust with very little margin for error. While there have been several proposed and prototyped IATs, only a few (such as the ones presented in this paper) have taken the crucial step of testing the device with clinical populations. However, even these tests remain small pilot trials; partially because people with cognitive disabilities are considered to be a vulnerable population, therefore prototype testing with this group remains a difficult and costly challenge for device developers. In response to these challenges, researchers are developing tactics to optimise device performance as much as possible before going to clinical trials, such as the use of actors to simulate older adults with dementia performing ADL and stunt actors to simulate falls [63,64].

The devices discussed in this paper only scratch the surface of the multitude of IATs that are currently under development. While most of the devices presented above are designed to support cognition using more-or-less a single angle of attack for a specific task and user group, consumers will likely implement several solutions to gain a broader range of support for their needs. Projects such as *openAAL*, an open source middleware platform, are underway to provide the necessary tools to enable data flow from multiple sensors or devices in an intelligent supportive environment [65]. Using a multisystem approach will create an intelligent home with the ability to provide holistic support ranging from guidance through tasks to identifying changes in health that could have otherwise gone unnoticed.

The IATs mentioned in this paper are able to provide continuous and tailored support with very little or no effort on the part of the user by autonomously monitoring the user, detecting when there is a problem, deciding on an appropriate response, and delivering information to appropriate parities in a meaningful way. IATs' ability to detect a situation and subsequently perform intelligent data processing and decision making is what makes IATs such powerful tools for the tracking and management of a person's well-being. IATs' ability to recognise different situations and take appropriate actions, often more quickly than human could, enable them to support or assume a variety of cognitive tasks, which is particularly useful for people who require assistance with reasoning and planning. IATs' flexibility enables them to fulfill different dynamic, supportive roles such as a continuous and increasing supportive memory tool in the case of progressive conditions, such as people with dementia, or as a teaching tool for people with conditions that can be rehabilitated, such as some cases of ABI. IATs are able to adjust to fit individuals' abilities and adapt to them if and when they change.

While the commercial implementation of IATs is just beginning, the considerable impact IATs could have on the lives of people with disabilities is already gaining attention internationally, causing shifts in policy regarding the acquisition and funding of this class of devices. As many of the devices presented in this paper can be costly, it is important that the support provided by IATs are objectively assessed so that the purchaser of an IAT (which can range from a private individual to insurance providers) can make an informed decision regarding potential return on investment. As the selection of IAT continues to grow and the population continues to age, this "cost versus support" quandary will gain significance. Objective measures of efficacy will become more prevalent as IATs are implemented with the general population.

Of course, ethical and privacy issues must be carefully considered, respected, and implicitly designed into devices at all stages in the development process [66]. It can be argued that since a computer (rather than a human) is capturing and analysing the data, many IAT applications may increase users' privacy so long as they remain transparent in how the resulting data is handled. The benefits of IATs are not only important for people with disabilities, but will almost certainly be useful to people in general, thereby greatly impacting society as a whole. If current trends continue, the next few decades will be remembered as the ones that introduced intelligent devices into our everyday lives.

Acknowledgements

The authors wish to thank Dr. Suzanne Martin, Dr. Tamara Hayes, and Tuck-Voon How for contributions regarding their research.

References

[1] A.M. Cook and J.M. Polgar, *Cook and Hussey's Assistive Technologies: Principles and Practice* (*3rd ed.*), Mosby: St. Louis, MO, 2007.

[2] S.J. Russell and P. Norvig, *Artificial Intelligence: A Modern Approach* (*Third Edition*), Prentice Hall: Upper Saddle River, N.J, 2010.

[3] T.L. Hayes, K. Cobbinah, T. Dishongh, J.A. Kaye, J. Kimel, M. Labhard, T. Leen, J. Lundell, U. Ozertem, M. Pavel, M. Philipose, K. Rhodes and S. Vurgun, A Study of Medication-Taking and Unobtrusive, Intelligent Reminding, *Telemedicine and e-Health* **15** (2009), 770–776.

[4] H. Kwok and P.W.H. Cheung, Co-morbidity of psychiatric disorder and medical illness in people with intellectual disabilities, *Current Opinion in Psychiatry* **20** (2007), 443–449.

[5] E.A. Bayliss, J.L. Ellis and J.F. Steiner, Barriers to self-management and quality-of-life outcomes in seniors with multimorbidities, *Annals of Family Medicine* **5** (2007), 395–402.

[6] N.R. Chumbler, B. Neugaard, R. Kobb, P. Ryan, H. Qin and Y. Joo, Evaluation of a care coordination/home-telehealth program for veterans with diabetes: health services utilization and health-related quality of life, *Evaluation and the Health Professions* **28** (2005), 464–478.

[7] L.M. Orlov, Health-Based Technology in the Home: Why it Matters, Why Now, *Journal of Geriatric Care Management* **20** (2010), 4–8.

[8] F.A. Sorond, A. Galica, J.M. Serrador, D.K. Kiely, I. Iloputaife, L.A. Cupples and L.A. Lipsitz, Cerebrovascular hemodynamics, gait, and falls in an elderly population: MOBILIZE Boston Study, *Neurology* **74** (2010), 1627–1633.

[9] G. Abellan van Kan, Y. Rolland, S. Andrieu, P. Anthony, J. Bauer, O. Beauchet, M. Bonnefoy, M. Cesari, L.M. Donini, S. Gillette-Guyonnet, M. Inzitari, I. Jurk, F. Nourhashemi, E. Offord-Cavin, G. Onder, P. Ritz, A. Salva, M. Visser and B. Vellas, Gait Speed at usual pace as a predictor of adverse outcomes in community-dwelling older people, *Journal of Nutrition, Health and Aging* **13** (2009), 881–889.

[10] J. Afilalo, M.J. Eisenberg, J.-F. Morin, H. Bergman, J. Monette, N. Noiseux, L.P. Perrault, K.P. Alexander, Y. Langlois, M. Gharacholou, P. Chamoun, G. Kasparian, S. Robichaud and J.-F. Boivin, Gait Speed as a Predictor of Mortality and Major Morbidity in Older Adults Undergoing Cardiac Surgery: Preliminary Results From the FRAILTY ABC'S Study, *Circulation* **120** (2009), S988–S989.

[11] J.A. Kaye, S.A. Maxwell, N. Mattek, T. L. Hayes, H. Dodge, M. Pavel, H. Jimison, K. Wild, L. Boise and T. Zitzelberger, Intelligent Systems for Assessing Aging Changes: Home-Based, Unobtrusive and Continuous Assessment of Aging, *Journal of Gerontology; Series B: Psychological Sciences* (2010), in press.

[12] T.L. Hayes, M. Pavel and J. Kaye, An approach for deriving continuous health assessment indicators from in-home sensor data, in: *Technology and Aging, vol. 21, Assistive Technology Research Series*, A. Mihailidis, J. Boger, H. Kautz and L. Normie, eds, IOS Press: 2008, pp. 130–137.

[13] T.L. Hayes, F. Abendroth, A. Adami, M. Pavel, T.A. Zitzelberger and J.A. Kaye, Unobtrusive assessment of activity patterns associated with mild cognitive impairment, *Alzheimer's and Dementia* **4** (2008), 395–405.

[14] S. Hagler, D. Austin, T. L. Hayes, J. Kaye and M. Pavel, Unobtrusive and Ubiquitous In-Home Monitoring: A Methodology for Continuous Assessment of Gait Velocity in Elders, *IEEE Transactions on Biomedical Engineering* (2010), in press.

[15] T.L. Hayes, T. Riley, M. Pavel and J.A. Kaye, A method for estimating rest-activity patterns using simple pyroelectric motion sensors, presented at *32nd Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Buenos Aires, Argentina, 2010.

[16] M. Skubica, G. Alexander, M. Popescuc, M. Rantzb and J. Kellera, A smart home application to eldercare: Current status and lessons learned, *Technology and Health Care* **17** (2009), 183–201.

[17] B.A. Majeed and S.J. Brown, Developing a well-being monitoring system-Modeling and data analysis techniques, *Applied Soft Computing Journal* **6** (2006), 384–393.

[18] K. Park, Y. Lin, V. Metsis, Z. Le and F. Makedon, Abnormal Human Behavioral Pattern Detection in Assisted Living Environments, presented at *PETRA*, Samos, Greece, 2010.

[19] T. Suzuki and S. Murase, Influence of Outdoor Activity and Indoor Activity on Cognition Decline: Use of an Infrared Sensor to Measure Activity, *Telemedicine and e-Health* **16** (2010), 686–690.

[20] SMARTRISK, *The Economic Burden of Injury in Canada*, SMARTRISK, 2009.

[21] S. Heinrich, K. Rapp, U. Rissmann, C. Becker and H.-H. König, Cost of falls in old age: a systematic review, *Osteoporos International* **21** (2009), online.

[22] J. Snoek, J. Hoey, L. Stewart, R. Zemel and A. Mihailidis, Automated detection of unusual events on stairs, *Image and Vision Computing* **27** (2009), 153–166.

[23] B.E. Maki, S.D. Perry, C.Y. Scovil, A.L. Peters, S.M. McKay, T.A. Lee, P. Corbeil, G.R. Fernie and W.E. McIlroy, Interventions to promote more effective balance-recovery reactions in industrial settings: new perspectives on footwear and handrails, *Industrial Health* **46** (2008), 40–50.

[24] J. Davison and S. Marrinan, Falls, *Reviews in Clinical Gerontology* **17** (2007), 93–107.

[25] National Center for Injury Prevention and Control: Division of Unintentional Injury Prevention, Costs of Falls Among Older Adults, Centers for Disease Control and Prevention, Department of Health and Human Services: Atlanta, GA, http://www.cdc.gov/ncipc/factsheets/fallcost.htm, 2008 (Accessed on: 13 August 2010).

[26] E.J. Porter, Wearing and using personal emergency response systems, *Journal of Gerontological Nursing* **31** (2005), 26–33.

[27] J. Fleming and C. Brayne, Inability to get up after falling, subsequent time on floor, and summoning help: prospective cohort study in people over 90, *BMJ* **337** (2008), a2227 (online).

[28] B. Schulze, M. Floeck and L. Litz, Concept and Design of a Video Monitoring System for Activity Recognition and Fall Detection, presented at *7th International Conference on Smart Homes and Health Telematics* (*ICOST*), Tours, France, 2009.

[29] M. Grassi, A. Lombardi, G. Rescio, P. Malcovati, M. Malfatti, L. Gonzo, A. Leone, G. Diraco, C. Distante, P. Siciliano, V. Libal, J. Huang and G. Potamianos, A hardware-software framework for high-reliability people fall detection, *IEEE Sensors* **26–29** (2008), 1328–1331.

[30] C. Doukas, I. Maglogiannis, A. Rouskas and A. Pneumatikakis, Emergency incidents detection in assisted living environments utilizing sound and visual perceptual components, presented at *PETRA*, Corfu, Greece, 2009.

[31] M. Hamill, V. Young, J. Boger and A. Mihailidis, Development of an Automated Speech Recognition Interface for Personal Emergency Response Systems, *Journal of NeuroEngineering and Rehabilitation* **6** (2009), online.

[32] T. Lee and A. Mihailidis, An intelligent emergency response system, *Journal of Telemedicine and Telecare* **11** (2005), 194–198.

[33] J. Snoek, B. Taati and A. Mihailidis, Automated detection of falls in the home: Current challenges and future directions, presented at *International Society for Gerontechnology* (*ISG*) *7th World Conference*, Vancouver, BC, 2010.

[34] L. Liao, D.J. Patterson, D. Fox and H. Kautz, Learning and inferring transportation routines, *Artificial Intelligence* **171** (2007), 311–331.

[35] A.L. Liu, G. Borriello, H. Kautz, P.A. Brown, M. Harniss and K. Johnson, Learning User Models to Improve Wayfinding Assistance for Individuals with Cognitive Impairment, presented at *Workshop on Interactive Systems in Healthcare*, Atlanta, GA, 2010.

[36] S. Oung, Location Assistance for Individuals with Traumatic Brain Injury, *B.A.Sc.*(*Eng.*) *dissertation*, University of Toronto Toronto, ON, 2010.

[37] R.C. Simpson, R.A. Cooper and E.F. LoPresti, How many people would benefit from a smart wheelchair? *Journal of Rehabilitation Research and Development* **45** (2008), 53–72.

[38] R. Ceres, J.L. Pons, L. Calderon, A.R. Jimenez and L. Azevedo, A robotic vehicle for disabled children, *IEEE Engineering in Medicine and Biology Magazine* **24** (2005), 55–63.

[39] L. Montesano, M. Diaz, S. Bhaskar and J. Minguez, Towards an Intelligent Wheelchair System for Users with Cerebral Palsy, *IEEE Transactions on Neural Systems and Rehabilitation Engineering* **18** (2010), 193–202.

[40] T.-V. How and A. Mihailidis, Anti-collision and navigation system for powered wheelchairs, presented at *International Society for Gerontechnology* (*ISG*) *7th World Conference*, Vancouver, BC, 2010.

[41] P. Viswanathan, J.J. Little, A. Mackworth and A. Mihailidis, The Future of Powered Mobility: Intelligent Wheelchairs, presented at *International Society for Gerontechnology* (*ISG*) *7th World Conference*, Vancouver, BC, 2010.

[42] P. Viswanathan, T. Southey, J.J. Little and A. Mackworth, Automated place classification using object detection, presented at *Canadian Robot Vision*, Ottawa, ON, 2010.

[43] A.K. Desai, G.T. Grossberg and D.N. Sheth., Activities of daily living in patients with dementia: clinical relevance, methods of assessment and effects of treatment, *CNS Drugs* **18** (2004), 853–875.

[44] P. Clarke, V. Marshall, S.E. Black and A. Colantonio, Well-being after stroke in Canadian seniors: Findings from the Canadian Study of Health and Aging, *Stroke* **33** (2002), 1016–1021.

[45] M. Kreuter, M. Sullivan, A.G. Dahlloöf and A. Sioösteen, Partner relationships, functioning, mood and global quality of life in persons with spinal cord injury and traumatic brain injury, *Spinal Cord* **36** (1998), 252–261.

[46] J. Bauchet, H. Pigot, G. Sylvain, L.-D. Dany, L. Yves and M. Mounir, Designing judicious interactions for cognitive assistance: the acts of assistance approach, presented at *11th international ACM SIGACCESS Conference on Computers and Accessibility*, Pittsburgh, Pennsylvania, USA, 2009.

[47] J. Bauchet, S. Giroux, H. Pigot, D. Lussier-Desrochers and Y. Lachapelle, Pervasive assistance in smart homes for people with intellectual disabilities a case study on meal preparation, *International Journal of Assistive Robotics and Mechatronics* **9** (2008), 42–54.

[48] J. Hoey, P. Poupart, A. von Bertoldi, T. Craig, C. Boutilier and A. Mihailidis, Automated Handwashing Assistance For Persons With Dementia Using Video and A Partially Observable Markov Decision Process, *Computer Vision and Image Understanding – Special Issue on Computer Vision Systems* **114** (2010), 503–519.

[49] A. Mihailidis, J. Boger, M. Canido and J. Hoey, The use of an intelligent prompting system for people with dementia: A case study, *ACM Interactions* (*Special Issue on Designing for Seniors: Innovations for Graying Times*) **14** (2007), 34–37.

[50] A. Mihailidis, J. Boger, T. Craig and J. Hoey, The COACH prompting system to assist older adults with dementia through handwashing: An efficacy study, *BMC Geriatrics* **8** (2008).

[51] A. Mihailidis, J.C. Barbenel and G.R. Fernie, The efficacy of an intelligent cognitive orthosis to facilitate handwashing by persons with moderate-to-severe dementia, *Neuropsychological Rehabilitation* **14** (2004), 135–171.

[52] V. Monroy, A Wizard-of-Oz Study to Determine the Efficacy of an Automated Prompting System for Children with Autism, *M.A.Sc.*(*Eng.*) *dissertation*, University of Toroto: Toronto, ON, 2010.

[53] J. Killick and K. Allan, *Communication and the Care of People with Dementia*, Open University Press: Buckingham, UK, 2001.

[54] J. Rusted, L. Sheppard and D. Waller, A Multi-centre Randomized Control Group Trial on the Use of Art Therapy for Older People with Dementia, *Group Analysis* **39** (2006), 517–536.

[55] P. Baines, *Nurturing the Heart: Creativity, art Therapy and Dementia*, Alzheimer's Australia, 2007.

[56] A. Mihailidis, S. Blunsden, J. Boger, B. Richards, K. Zutis, L. Young and J. Hoey, Towards the Development of a Technology for Art Therapy and Dementia: Definition of Needs and Design Constraints, *The Arts in Psychotherapy* **In Press** (2010), 4.

[57] BRAIN project, EU-project BRAIN (ICT-2007-224156), Bremen, Germany, http://www.brain-project.org, (Accessed on: 14 August 2010).

[58] H. Gollee, I. Volosyak, A.J. McLachlan, K.J. Hunt and A. Gräser, An SSVEP based Brain-Computer Interface for the control of functional electrical stimulation, *IEEE Transactions on Biomedical Engineering* **57** (2010), 1847–1855.

[59] G. Garcia-Molina, T. Tsoneva and A. Nijholt, Emotional brain-computer interfaces, presented at *3rd International Conference on Affective Computing and Intelligent Interaction and Workshops* (*ACII*), Amsterdam, the Netherlands, 2009.

[60] E.Thomson, S. Mathews, D.Todd, P.J.M. Cullagh, M.P. Ware, M.D. Mulvenna and S. Martin, BRAIN: Developing brain computer interfaces with rapid automated interfaces for non-experts, presented at *International Society for Gerontechnology* (*ISG*) *7th World Conference*, Vancouver, Canada, 2010.

[61] K. Tai, S. Blain and T. Chau, A review of emerging access technologies for individuals with severe motor impairments, *Assistive Technology* **20** (2008), 204–219.

[62] S. Blain, S.D. Power, E. Sejdic, A. Mihailidis and T. Chau, A cardiorespiratory classifier of voluntary and involuntary electrodermal activity, *BioMedical Engineering OnLine* **9** (2010), on line.

[63] J. Boger, J. Hoey, K. Fenton, T. Craig and A. Mihailidis, Using actors to develop technologies for older adults with dementia: A pilot study, *Gerontechnology* **9** (2010), 450–463.

[64] M.J. Rantz, M.A. Aud, G. Alexander, B.J. Wakefield, M. Skubic, R. Luke, D. Anderson and J. Keller, Falls, Technology, and Stunt Actors: New Approaches to Fall Detection and Fall Risk Assessment, *Journal of Nursing Care Quality* **23** (2008), 195–201.

[65] P. Wolf, A. Schmidt, J.P. Otte, M. Klein, S. Rollwage, B. König-Ries, T. Dettborn and A. Gabdulkhakova, openAAL – the open source middleware for ambient-assisted living (AAL) presented at *AALIANCE conference*, Malaga, Spain, 2010.

[66] Information and Privacy Commissioner of Ontario (Canada), *Sensors and In-Home Collection of Health Data: A Privacy by Design Approach*, Information and Privacy Commissioner, 2010.