UNIVERSITAT DE BARCELONA

Context-aware quality of life telemonitoring for a novel healthcare paradigm

Felip Miralles Barrachina

UNIVERSITAT DE BARCELONA

DOCTORAL THESIS

Context-aware Quality of Life telemonitoring for a novel healthcare paradigm

Author:
Felip MIRALLES BARRACHINA

Supervisor:
Dr. Petia RADEVA

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

in the

Faculty of Mathematics and Computer Science
Doctoral program of Engineering and Advanced Technologies

January 14, 2016

UNIVERSITAT DE BARCELONA

Declaration of Authorship

I, Felip MIRALLES BARRACHINA, declare that this thesis titled, 'Context-aware Quality of Life telemonitoring for a novel healthcare paradigm' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed: ____________________________________

Date: ____________________________________

"The quality of life is determined by its activities."

Aristotle

"To affect the quality of the day, that is the highest of arts."

Henry David Thoreau

"The part of life we really live is small. For all the rest of existence is not life, but merely time."

Seneca

UNIVERSITAT DE BARCELONA

Abstract

Faculty of Mathematics and Computer Science
Doctoral program of Engineering and Advanced Technologies

Doctor of Philosophy

Context-aware Quality of Life telemonitoring for a novel healthcare paradigm

by Felip MIRALLES BARRACHINA

Our healthcare systems are facing sustainability challenges caused by a demographic shift with ageing, chronicity and disability growing in our society. A novel healthcare paradigm should be founded on 4P medicine: Preventive, Predictive, Personalized, and Participatory medicine needs new methodologies and tools enabled by Information and Communication Technologies (ICTs). One of the key technology enablers for 4P medicine is telemonitoring, i.e. ICTs to monitor the health status of a patient from a distance, which may trigger 4P decision making. A new generation of telemonitoring tools allow prescription and follow-up around the main chronic care strategies, namely, therapeutic adherence and healthy habits promotion. A broader and more ambitious challenge is Quality of Life (QoL) telemonitoring based on the knowledge of context. We are proposing a formal methodology to provide Context-aware QoL assessment, categorizing data inputs, defining outputs, and exploring data fusion techniques. A Telemonitoring and Home Support System (TMHSS) which implements that methodology has been designed, developed and integrated to the BackHome system for a particular Use Case, i.e. severely disabled people using Brain Computer Interfaces (BCI) as an assistive technology (AT) at home. We have applied User Centred Design throughout all development stages of a multi-functional BCI, in order to move BCIs from the lab towards independent home use. The BackHome system has achieved five key innovations: (i) an architecture able to meet the requirements of BCI multifunctionality and remote home support; (ii) a light, autonomous, comfortable and reliable BCI equipment; (iii) an easy-to-use software to control multiple purpose applications; (iv) a TMHSS for BCI independent home use; and (v) a Therapist station to manage and monitor BCI-based remote services. We have evaluated the BackHome system with end-users at home, also taking the therapists' and non-expert caregivers' perspective into account. The results show good acceptance, usability levels, user satisfaction and levels of control, which demonstrate that BCI can already be considered as an alternative AT. We used the TMHSS of BackHome to recognize activities and habits of users based on the analysis of sensors' data, in order to detect for example whether the user is at home or away or whether has received a visit at home or not. Similarly, and consequently from the previous analysis, results show good accuracies in assessing items of QoL such as Mobility, Sleep, or Mood, based on measures and fusion of detected activities from the user. The assessment of the overall wellbeing of an individual with a multidimensional perspective through processing of data gathered from environmental and personal sensors in a broad and non-intrusive way, will become of great interest to healthcare professionals, policy makers and also for citizens which are called to co-produce and lead the new paradigm of care.

UNIVERSITAT DE BARCELONA

Resum

Facultat de Matemàtiques i Informàtica
Programa de doctorat d'Enginyeria i Tecnologies Avançades

Doctor en Filosofia

Telemonitoratge contextual de la Qualitat de Vida per a un nou paradigma de salut

per Felip MIRALLES BARRACHINA

Els nostres sistemes de salut estan veient qüestionada la seva sostenibilitat arran del canvi demogràfic d'una societat en la qual augmenta la prevalença de cronicitat i discapacitat. El nou model de salut es basa en la Medicina 4P: la medicina Preventiva, Predictiva, Personalitzada i Participativa necessita de nous serveis habilitats per les Tecnologies d'Informació i Comunicació (TIC). Una tecnologia clau per a la Medicina 4P és el telemonitoratge, és a dir, les TIC per conèixer l'estat de salut d'un pacient a distància i prendre decisions 4P. Una nova generació d'eines de telemonitoratge facilita estratègies de gestió de la cronicitat, a saber, l'adherència al tractament terapèutic i la promoció d'hàbits saludables. Un repte més ampli i ambiciós és el telemonitoratge de la Qualitat de Vida (QoL) basat en el coneixement del context. Proposem una metodologia formal per avaluar la QoL mitjançant la categorització de dades d'entrada i sortida i tècniques de fusió de dades. Hem dissenyat i desenvolupat un Sistema de Telemonitoratge i Suport Domiciliari (TMHSS) que implementa aquesta metodologia, integrat al sistema BackHome per un Cas d'Ús concret, el de persones amb discapacitats severes que utilitzen Interfícies Cervell Ordinador (BCI) a casa seva com a Tecnologia Assistencial (AT) . Hem aplicat Disseny Centrat en l'Usuari amb la finalitat de traslladar els BCIs des del laboratori fins a l'ús domèstic independent. El sistema BackHome ha assolit cinc innovacions fonamentals: (i) una arquitectura que satisfà els requisits d'un BCI multifuncional i amb suport remot; (ii) un dispositiu de BCI lleuger, autònom, còmode i fiable; (iii) un programari fàcil d'utilitzar per a manegar diverses aplicacions d'autonomia física i social; (iv) Un TMHSS per fer efectiu l'ús independent dels BCIs a la llar; i (v) una estació clínica per a la gestió remota de serveis terapèutics. Hem avaluat el sistema BackHome amb usuaris finals a casa seva, aprenent de la perspectiva de terapeutes i cuidadors no experts amb resultats que mostren bona acceptació i nivells d'usabilitat, satisfacció de l'usuari i nivells de control que demostren que el BCI pugui ja considerar-se una AT alternativa. Hem emprat el TMHSS de BackHome en el reconeixement d'activitats i hàbits dels usuaris a partir de l'anàlisi de dades de sensors, per detectar per exemple si l'usuari està a casa o fora, o si ha rebut una visita. També hem avaluat a continuació amb bona precisió elements de la Qualitat de Vida, com ara mobilitat, son, o estat d'ànim, a partir de les activitats de l'usuari prèviament detectades. L'avaluació del benestar general i l'estat de salut d'una persona a partir del processament de dades de sensors ambientals i personals no intrusius, serà de gran interès per a professionals i gestors de salut i també per als ciutadans que estan cridats a coproduir i liderar un nou model de salut.

UNIVERSITAT DE BARCELONA

Resumen

Facultad de Matemáticas e Informática
Programa de doctorado de Ingeniería y Tecnologías Avanzadas

Doctor en Filosofía

Telemonitorización contextual de Calidad de Vida para un nuevo modelo de salud

por Felip MIRALLES BARRACHINA

Nuestros sistemas de salud están viendo cuestionada su sostenibilidad a raíz del cambio demográfico de una sociedad en la que cronicidad y discapacidad aumentan su prevalencia. El nuevo modelo de salud se basa en la Medicina 4P: la medicina Preventiva, Predictiva, Personalizada y Participativa necesita de nuevos servicios habilitados por las Tecnologías de Información y Comunicación (TIC). Una tecnología clave para la Medicina 4P es la telemonitorización, es decir, las TIC para conocer el estado de salud de un paciente a distancia y tomar decisiones 4P. Una nueva generación de herramientas de telemonitorización facilita estrategias de gestión de la cronicidad, a saber, la adherencia al tratamiento terapéutico y la promoción de hábitos saludables. Un desafío más amplio y ambicioso es la telemonitorización de la Calidad de Vida (QoL) basada en el conocimiento del contexto. Hemos propuesto una metodología formal para evaluar la QoL mediante categorización de datos de entrada y salida y técnicas de fusión de datos. Hemos diseñado y desarrollado un Sistema de Telemonitorización y Soporte Domiciliario (TMHSS) que implementa esta metodología, integrado al sistema BackHome para un Caso de Uso concreto, el de personas con discapacidad severa que utilizan Interfaces Cerebro Ordenador (BCI) como tecnología asistencial (AT) en entornos reales. Hemos aplicado Diseño Centrado en el Usuario con la finalidad de trasladar los BCIs desde el laboratorio hasta el uso doméstico independiente. El sistema BackHome aporta cinco innovaciones fundamentales: (i) una arquitectura que cumple con los requisitos de un BCI multifuncional y con soporte remoto; (ii) un dispositivo de BCI ligero, autónomo, cómodo y fiable; (iii) un software fácil de usar para manejar múltiples aplicaciones de autonomía física y social; (iv) un TMHSS para hacer efectivo el uso independiente del BCI; y (v) una estación para la gestión remota de servicios terapéuticos. Hemos evaluado el sistema BackHome con usuarios finales en su propia casa, aprendiendo de la perspectiva de terapeutas y cuidadores no expertos con resultados que muestran buena aceptación y niveles de usabilidad, satisfacción del usuario y niveles de control que demuestran que el BCI puede ya considerarse una AT alternativa. Hemos utilizado el TMHSS de BackHome en el reconocimiento de actividades y hábitos de los usuarios a partir del análisis de datos de sensores, para detectar por ejemplo si el usuario está en casa o no, o si ha recibido una visita. También hemos evaluado a continuación elementos de la Calidad de Vida, tales como movilidad, sueño, o estado de ánimo, a partir de las actividades del usuario previamente detectadas. La evaluación del bienestar general de una persona a partir del procesamiento de datos de sensores ambientales y personales no intrusivos será de gran interés para profesionales y gestores de salud y también para los ciudadanos que están llamados a coproducir y liderar un nuevo modelo de salud.

Acknowledgements

Thanks to Dr. Petia Radeva, my supervisor, for her invaluable advice and support. Thanks to the eHealth team at Barcelona Digital recently transformed into Eurecat: firstly, and specially, Dr. Eloisa Vargiu and Xavier Rafael-Palou, who have in fact made possible the excellent outcomes of the BackHome project with their talent and passion, leading technical development, data analytics and interrelation of technologies; also, Stefan Dauwalder, Marc Solà, Juan Manuel Fernández, Alex Steblin, Eloi Casals, José Alejandro Cordero, Carme Zambrana, Joan Protasio, Jordi Roda, Javier Bautista and Jesús Fernández, they all contributed their highly specialized skills with outstanding creativity and proactivity in BackHome to achieve all the ambitious goals of the project; then, a team mention to the other talented researchers of the eHealth team, Laia Subirats, Silvia Orte, Filip Velickovski, Magí Lluch, David Marí,..., we have done great things together these recent years. Thanks and acknowledgements to the rest of the BackHome consortium: Jean Daly, Suzanne Martin, Elaine Armstrong at Cedar Foundation, who were in charge of user centered design and validation ; Christoph Hintermüller, Arnau Espinosa, Christoph Guger at g.tec, who designed and developed the BCI hardware and control software and were in charge of integration; Selina Wriessnegger, Andreas Pinegger, Gernot Müller-Putz at Technische Universität Graz, who were leading BCI research and development; Ivo Käthner, Sebastian Hälder, Andrea Kübler at Universität Würzburg, who contributed to BCI research and development and were leading the validation process; and Hannah Lowish and Donald Markey at Medvivo, who were in charge of integration with their telehealth solutions and were leading dissemination and exploitation activities. Special thanks to my good friend Dr. Brendan Allison, who introduced me to BCIs and other spices. Special thanks to Dr. Josep Roca, Dr. Joan Escarrabill and Dr. Josep Maria Tormos, they inoculated me the virus of research and innovation in Digital Health.

Contents

List of Figures

List of Tables

List of Abbreviations

4P Medicine	**P**reventive, **P**redictive, **P**ersonalized and **P**articipatory **Medicine**
ABI	**A**cquired **B**rain **I**njury
ACTOR	**A**pplication **C**on**T**rol and **O**nline **R**econfiguration protocol
ADL	**A**ctivities of **D**aily **L**iving
ALS	**A**myotrophic **L**ateral **S**clerosis
AmI	**Am**bient **I**ntelligence
API	**A**pplication **P**rogramming **I**nterface
AT	**A**ssistive **T**echnology
BCI	**B**rain **C**omputer **I**nterface
BNCI	**B**rain **N**eural **C**omputer **I**nterface
ECG	**E**lectro**C**ardio**G**raphy
EEG	**E**lectro**E**ncephalo**G**raphy
EHR	**E**lectronic **H**ealth **R**ecord
EMG	**E**lectro**M**yo**G**raphy
ESB	**E**nterprise **S**ervice **B**us
EOG	**E**lectro**O**culo**G**raphy
ERP	**E**vent **R**elated **P**otentials
GSR	**G**alvanic **S**kin **R**esponse
HRQoL	**H**ealth **R**elated **Q**uality **o**f **L**ife
HTTP	**H**yper**t**ext **T**ransfer **P**rotocol
IC	**I**ntegrated **C**are
ICD-10	**I**nternational **C**lassification of **D**iseases version **10**
ICF	**I**nternational **C**lassification of **F**unctioning, disability and health
ICT	**I**nformation and **C**ommunication **T**echnology
IM	**I**ntelligent **M**onitoring
ITR	**I**nformation **T**ransfer **R**ate
NS	**N**otification **S**ervice
PHF	**P**ersonal **H**ealth **F**older
PUI	**P**rimary **U**ser **I**nterface
QoL	**Q**uality **o**f **L**ife
SNOMED CT	**S**ystematized **No**menclature of **Med**icine **C**linical **T**erms
SM	**S**ecurity **M**anager
SoA	**S**ervice-**o**riented **A**rchitecture
SOCI	**S**creen **O**verlay **C**ontrol **I**nterface
TMHSS	**T**ele**m**onitoring and **H**ome **S**upport **S**ystem
UCD	**U**ser **C**entered **D**esign
UMLS	**U**nified **M**edical **L**anguage **S**ystem
UUID	**U**niversally **U**nique **ID**entifier
VAS	**V**isual **A**nalogue **S**cale
vMR	**v**irtual **M**edical **R**ecord
WHO	**W**orld **H**ealth **O**rganization

For the quality of life of people I love: my wife María, my son Marcel and my daughter Joana; my father Felipe and my mother Laure (who cared for all of us); my sisters Olga and Sandra; all relatives, friends and inspiring folks inhabiting my heart…

Chapter 1

Introduction

1.1 Motivation

The eHealth term was coined about 15 years ago when this discipline in the convergence of Life Sciences and Engineering was born [1]. But it is just now when we are fully entering in the radical transformation of medicine and healthcare practice enabled by Information and Communication technologies (ICTs). The Economist announced it in the change of decade 2010 with its special issue *Medicine goes digital* [2], when at the age of smartphones and tablets the derived term mHealth became popular and added new possibilities to personalization and ubiquity of health.

We come from an important technological investment in the digitalization of data, images and processes. Professionals at hospitals, primary care centers, pharmacy offices, social-sanitary residences and administrations are regularly checking and updating *Electronic Health Records (EHR)*, radiologic images, or endoscopy videos, which are stored and transferred in standard formats which facilitate security and interoperability. Thanks to those efforts, new commodities are being progressively deployed, such as *ePrescription*, which facilitate drug prescription and delivery; *Personal Health Folders (PHF)* for citizens to check up their health information, check results of blood analytics, schedule visits or carry out other simple transactions with their health providers; and *telemedicine applications* for patients and remote or isolated healthcare centers to connect to highly specialized health resources.

But this is not enough. The crisis of 2008, which has provoked structural and global changes with uncertainties about the future and suffering for major population groups, has even further questioned the sustainability of the healthcare systems as we knew them. Short term solutions have emerged like the co-payment by citizens of emergency services and drugs; reductions in beds, staff and surgery rooms; and privatization of care providers. These measures will not solve long-term sustainability and could worsen the quality of services and their perception by citizens. The problem is structural, and the right approach requires deep, disruptive and imaginative innovations to tackle the root of the problem, namely, the demographic shift that is menacing our aging society and that will intensify in the coming years. The demographic trend of our aging society is partly due to the amazing progress of medicine in the last decades, which has increased life expectancy and improved quality of life, specially for people living in developed countries. However, this demographic shift comes along with an important stress to our healthcare systems, which nowadays face sustainability challenges. The increasing number of chronic patients due to population aging, often complex and with comorbidities, although benefiting from a greater life expectancy and quality of life than before, are bringing heavy economic and social burdens in the shape of hospital re-admissions, expensive medications, periodic testing, and dependence, among others.

A threat lies here which could lead to collapse. But an opportunity is coming hand by hand at good time to transform healthcare and industry of health technology. The solution is certainly complex, since it requires a new paradigm of health with organizational, training, technology and business changes to promote radical efficiency and effectiveness. The new medicine has been described as 4P: personalized, preventive, predictive and participatory. It requires transformation from analogical to digital. From face to face to virtual. A transformation to improve patient experience. Now it is time to move from pilots, which have already been too many, to implementation of structural changes enabled by technological solutions which will transform healthcare systems to make them sustainable also improving health care quality. Not to mention that, of course, healthcare professionals with their knowledge and dedication will continue to make it possible. Healthcare can not be simplified as automation of industrial production processes.

The design of solutions which take advantage of new ICTs will provide efficiency, efficacy and cost-effectiveness to care practice. Telemedicine solutions allow to treat chronic patients living at home, preventing and predicting exacerbations and decreasing costly hospitalizations. Telerehabilitation solutions enable to follow up continuous interventions which may improve health conditions without the need for the patient to physically move to specialized facilities. Teleassistance solutions facilitate to improve autonomy, safety and social participation of people with special needs, namely the elderly and in particular the disabled, through home support technologies which avoid or at least postpone social-sanitary services and associated costs [3] (see Figure 1.1).

One key common feature of all those novel eHealth solutions is telemonitoring, i.e ICTs to monitor the health status of a patient from a distance which makes possible to remotely assess health status of individuals and ultimately trigger 4P decision making [4] [5]. By acquiring heterogeneous data coming from the Internet of Things (physiological, biometric, environmental sensors; non invasive, adaptive sensors transparent to the user) and data coming from other sources (e.g., interaction of the user with digital services) to become aware of user context; by inferring user behavior and detecting anomalies from this Big Data; and by providing elaborated and smart knowledge to clinicians, therapists, carers, families, and patients themselves, we will be able to foster preventive, predictive, shared and personalized care actions, decisions and support.

Thus, State of Art telemonitoring involves Big Data collection and processing of physiological signals and scales answered by patients and results presented to the clinician [6]. A new generation of telemonitoring tools allow therapy prescription and follow-up around the main chronic care strategies, namely, therapeutic adherence, and promotion of physical activity, good nutrition and healthy habits.

Recently, we proposed a methodology to collect, normalize and measure data coming from standardized scales which patients input regularly with the support of caregivers and clinicians [7]. This methodology provides metrics to assess the evolution of the health status of an individual, compare it with others, and even provide decision support in intervention planning [8][9]. A broader and more ambitious challenge,

FIGURE 1.1: Active and Healthy Aging through Teleassistance services in our SAAPHO project (http://www.saapho-aal.eu/).

which we will explore and advance in this thesis, is Quality of Life (QoL) telemonitoring based on the knowledge of context [10][11][12]: for this purpose, we will present a new generic methodology to telemonitor QoL of individuals with a holistic bio-psycho-social approach, which intends to become the base for current and future telemedicine and teleassistance solutions.

The main goal of this thesis will therefore be the description, implementation and validation of this methodology to pervasively assess QoL of individuals in the context of an assistive environment that provides home support to people with disabilities: in order to achieve our main goal, we will design and develop the BackHome system, which aims to improve physical and social autonomy of people with severe disabilities, for example after having been discharged from a neuro-rehabilitation hospital. In fact, the BackHome system aims to facilitate the transition from hospital to home. BackHome is a highly innovative solution which brings Brain Computer Interfaces (BCI) for the first time to end-users' homes as an alternative Assistive Technology (AT). One of the key innovations of the BackHome system is its telemonitoring and home support system (TMHSS) to remotely monitor and assist BCI independent home use, which offers remote services for therapists to assess the QoL of the end user at home, among other types of services. This Use Case at hand has one advantage: a severely disabled user needs to rely on AT in order to autonomously undertake most actions and tasks and might recognize sensors as part of the assistive and aiding technology. It also has a disadvantage, the high cost of equipment, especially BCI, and the uniqueness of the target end user at home, which will become a limitation and will force to have a limited number of end users in the experiments, which we will overcome with the implication of other types of users.

The assessment of the overall wellbeing of an individual with a multidimensional perspective through processing of Big Data gathered from environmental and personal 'Internet of Things' sensors in a broad and non-intrusive way, will become of great interest to healthcare professionals, policy makers and also for citizens which are called to co-produce and lead the new paradigm of care.

1.2 Background

Let us introduce here the concepts and foundations which we will research in this thesis, starting with the novel healthcare paradigm which will require innovative eHealth tools; then the concept of Quality of Life, the notion of context and finally the telemonitoring requirements and technologies.

1.2.1 Need for a novel healthcare paradigm - new eHealth solutions

European health and social care systems face major economic and quality issues if they are not significantly re-designed. An aging population and the increasing number of people with at least one chronic disease are demanding more resources and increasing the burden on health and social care systems.

Within these systems there is a lack of sufficient resources to meet these needs: therefore, ensuring a more sustainable and optimized use of resources and providing more efficient care, paying special attention to patients becoming active players throughout the whole care system, is of paramount importance. Integrated Care (IC) models are designed to respond to such challenges, through defragmentation of health and social care systems, promotion of collaboration and continuity among care settings, and a move from institutional, reactive care to a home-based, patient-centered, preventive model.

A number of different approaches have been proposed to address these IC issues but a comprehensive solution has not yet been achieved [13]. The necessary change management actions enabled by eHealth solutions to foster a novel paradigm of healthcare have been identified: a new organizational model for IC enabled by ICT tools for the adaptive case management of personalized clinical pathways, which takes into account the patient's medical history, socio-economic aspects, environmental constraints and the underlying context, to implement a proactive and preventive care approach. This novel model of care organization should connect all the professionals, patients themselves and their carers through integrated ICT solutions for all those actors to collaborate and communicate. IC is increasingly viewed as patient-centered care that is coordinated across settings and over time. By combining inputs from all the professionals and carers, ICT tools will support and empower the patient providing recommendations and suggestions according to a self-management approach, with continuous monitoring of the patient's activities and environment through the Internet of Things. The analysis of Big Data coming from that continuous monitoring will also be used to automatically assess the patient's status and quality of life enabling notifications for patients, carers and professionals regarding improvement or worsening of the patient's condition as well as alerts for carers and professionals in case emergency situations are detected, supporting 4P decisions.

1.2.2 Quality of Life

The World Health Organization (WHO) defines Quality of Life (QoL) as the individuals' perception on their position in life within the cultural context and the value system in which the individuals live and with respect to their goals, expectations, norms and worries [14]. It is a multidimensional and complex concept that includes personal aspects, like health, autonomy, independence, satisfaction with life and environmental aspects such as support networks and social services, among others.

QoL (sometimes refereed to as *Health-Related QoL* or HRQoL) is defined by the subjective experiences or preferences expressed by an individual, or members of a particular group of persons, in relation to specified aspects of health status that are meaningful, in definable ways, for that individual or group [15]. According to [16], QoL is a state of well-being defined by two components: (i) the ability to perform everyday activities, which reflects physical, psychological and social well-being, and patient satisfaction with levels of functioning, and (ii) the control of disease and treatment symptoms. Also, as [17] suggests, eHealth consumers are now empowered by an increased ability to obtain health information via the Internet, with the main objective to maintain the highest possible level of QoL.

1.2.3 Context

From the first time that the term context-aware computing was introduced by [18] in 1994 several definitions of context have been proposed. Among others, let us consider the definition by [19]: *"Context is any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves".*

This definition simplifies the concept of the information related to an interaction; avoiding the inclusion of information about other elements that can be at the scenario, without influencing the interaction between the user and the application. Following this definition, any information related to the involved elements can be used to characterize the context. Therefore, the context is the conjunction of specific data only related to the entities involved in the interaction.

In order to complement this definition, we are following the classification proposed by [20], which provides a natural understanding of the concept of context to users of context-aware applications and facilitates the engineering of this concept for software developers of such applications. This classification takes into account "five fundamental categories for context information": "Individuality Context", "Location Context", "Activity Context", "Relations context" and "Time Context".

1.2.4 Telemonitoring

A simple definition of telemonitoring is the one provided by the Institute of Medicine in the U.S.[21]: *"the remote monitoring of patients including the use of audio, video, and other telecommunications and electronic information processing technologies to monitor patient status at a distance"*.

As reported in [22], telemonitoring systems have been successful adopted in cardiovascular, hematologic, respiratory, neurologic, metabolic, and urologic activities [23]. In fact, some of the more common things that telemonitoring devices keep track of include blood pressure, heart rate, weight, blood glucose, and hemoglobin. Telemonitoring is capable of providing information about any vital signs, as long as patients have the necessary monitoring equipment at their location. In principle, a patient could have several monitoring devices at home. Clinical-care patients' physiologic data can be accessed remotely through the Internet and handled computers [24]. Depending on the severity of the patient's condition, the health care provider may check these statistics on a daily or weekly basis to determine the best course of treatment.

In addition to objective technological monitoring, most telemonitoring systems include subjective questioning regarding the patient's health and comfort [23]. This questioning can take place automatically over the phone, or telemonitoring software can help keep the patient in touch with the health care provider. The health care provider can then take decisions about the patient's treatment based on a combination of subjective and objective information similar to what would be revealed during an on-site appointment.

1.3 The BackHome project

Research efforts have improved Brain Computer Interface (BCI) technology in many ways and numerous applications for this alternative means of human computer interaction have been prototyped. Motivated by the aim of restoring independence to individuals with severe disabilities, the focus has centered on developing applications [25][26][27] for communication[28], movement control[29][30], environmental control[31], locomotion[32], as well as neurorehabilitation[33][34].

Until recently, though, these BCI systems had been researched almost exclusively in laboratories primarily with developers and sympathetic, enthusiastic populations, for example researchers; home usage has been demonstrated, though only with on-going expert supervision. A significant advance on BCI research and its implementation as a feasible assistive technology (AT) is therefore the migration of BCIs into people's homes to provide new options for communication and control that increase independence and reduce social exclusion. In this context, our BackHome[1] project was aimed at moving BCIs from being laboratory devices for healthy users toward practical systems used at home by people with severely limited mobility and/or cognitive impairment.

BCIs are devices that allow for communication and control via thought alone [35] [36] [37]. The term Brain Neural Computer Interface (BNCI) is broader than BCI, since BNCIs include systems that sense indirect measures of brain activity, and may not provide real-time feedback [38] [39] [40].

BackHome is partly based on the outcomes coming from our BrainAble[2] project, which aimed to deliver an ICT-based human-computer-interaction composed of a BNCI system combined with affective computing, virtual environments and the possibility to control heterogeneous devices like smart home environments and social networks [41]. BackHome advances BrainAble in supporting the transition from institutional care to home post rehabilitation and discharge [42].

BackHome aims to study the transition from the hospital to the home, focusing on how people use BNCIs in both settings. Moreover, it is aimed to learn how different BNCIs and other assistive technologies work together and can help clinicians, disabled people, and their families in the transition from the hospital to the home. The final goal

[1] www.Backhome-FP7.eu
[2] www.brainable.org

of BackHome is to reduce the cost and hassle of the transition from hospital to home by developing improved products, which include new and better integrated practical electrodes; friendlier and more flexible BNCI software; and better telemonitoring and home support tools.

1.3.1 A reference scenario

To better illustrate the objectives of BackHome and the need for the approach which will be presented in this thesis, let us illustrate a reference scenario[3].

Paul is a 60 years old man depressed about his recent stroke. Although Paul does not want to try new technologies, Dr. Jones suggests him to try to use a BNCI system at home, because he heard good things about the new BackHome system. Thus, Dr. Jones asks to Amanda – a nurse with over 10 years experience helping people in managing care environments and tools – to work with Paul. At the beginning, she says that she does not want to. In fact, in the past, she had a bad experience mounting a BCI cap, getting a new connection, and dealing with all the hassles of getting a BCI to work. Dr. Jones asks her to try again and Amanda visits Paul's home after having been trained one day to use the BackHome system. The first day, Amanda shows Paul how to use the BackHome system and how it is easy to perform different tasks. The second day, Paul decides to try it and, thanks to the friendly support tools, Amanda is easily able to find all the solutions to the encountered troubles. In the next days, through the telemonitoring system installed at Paul's home and the therapy station located at the hospital, Dr. Jones is able to continuously verify the status of Paul and to suggest him new and personalized exercises to his rehabilitation therapy. In few weeks, Paul becomes more motivated, performs the rehabilitation exercises daily, joins a chess club, and starts to talk online with friends. Through BackHome system, Dr. Jones notes the progresses in Paul's daily activities and in his mood, and the corresponding general improved quality of life. Thus, he decides to assign other nurses to introduce BackHome to further patients.

1.4 Research questions and contributions

A number of complementary research questions will drive the work presented in this thesis in which we will be advancing beyond State of Art innovations in the areas of User Centered Design (UCD), BCI as an alternative AT, telemonitoring and home support tools and context-aware QoL assessment. In particular we will structure the presentation of the work done around the following research questions and contributions:

- User Centered Design of a multifunctional BCI
- Acceptance of BCI-based AT by end users at home
- Activity recognition with the TMHSS
- Context-aware QoL telemonitoring
- Telemonitoring severely disabled people

This structure of 5 research questions and contributions will be addressed in the same way and order in Chapter 4 - Results and Chapter 5 - Discussion.

[3]Names have been completely made out for this reference purpose.

1.4.1 User Centered Design of a multifunctional BCI

The BackHome system aims to develop BCI systems into practical multimodal ATs to provide useful solutions for communication, Web access, leisure, cognitive stimulation and environmental control, and to provide this technology for home usage with minimal support.

The BackHome system will be designed with a User Centered Design (UCD) approach at the heart of the whole R&D process in order to move BCIs from the lab towards systems that are easy to use and can be operated by non-expert caregivers and target end users at home. In this R&D field, UCD has been proposed to bridge the translational gap between BCI systems and their target end users [43]. We will use UCD for the first time throughout all development stages of a multi-functional BCI and here lies one of the main innovation drivers of this thesis. Driven by this innovative UCD approach towards independent home use, the BackHome system is achieving five key innovations advancing the current state of the art: (i) a modular and distributed architecture able to meet the requirements of a multi-functional BCI with remote home support; (ii) a novel BCI equipment with practical electrodes aimed at setting a new standard of lightness, autonomy, comfort and reliability; (iii) easy-to-use software tailored to people's needs to manage a complete range of multifunctional applications finely tuned for one-click command and adaptive usage; (iv) a telemonitoring and home support system to remotely monitor and assist BCI independent use; and (v) a Web-based application for therapists which offers remote services to plan and monitor BCI-based cognitive rehabilitation and pervasively assess the quality of life (QoL) of the end-user at home among other advanced features, like the use of the BCI system by the end-user, for instance.

1.4.2 Acceptance of BCI-based AT by end users at home

A number of recent studies have indicated that BCIs could become useful solutions for the target end-user, however these studies have always been conducted in controlled environments or laboratory based ([44], [45], [46], [47]). We have just advanced in the previous research question how we are applying User Centered Design (UCD) as a way of reducing this gap between the laboratory and the real world use of BCI ([43]). Recently case studies have started to challenge these barriers and move BCI into the domestic environment ([48], [49], [50]). Limitations to home based testing include the cost of the systems, the difficulty of the set up, low response rate, the dependence on motivated caregivers, the need for technical support, the complexity of the software and hardware and the ethical implications. It was observed in [51] that because of the challenges associated with home based evaluations it is likely that numbers of end-users taking part will remain small. These studies have started to unpick the real world challenges that face BCIs when they are introduced to more complex environments, however further work is necessary to explore the realities of home use, and how that technology can be incorporated into the lives of end-users and their caregivers. Caregivers play a key role in bringing BCI towards home based solutions.

Following on from the work of [49], we will be incorporating a multimodal system aimed at moving BCIs into end-user homes and their non-expert caregivers. In particular, we will integrate the research in practical electrodes, easy to use software and home support aids into an innovative multimodal AT which will provide useful services for communication, Web access, cognitive rehabilitation, leisure, and environmental control with non-expert support. In [52] we illustrate the framework adopted in the design and development of the BackHome system incorporating a UCD approach.

In this thesis, we will also assess the end-user's satisfaction with this unique BCI-based AT, presenting and discussing the results from the home evaluation of the system with people living with acquired brain injury. To our knowledge, this is the first time a BCI with such a wide range of functionalities has been evaluated at home by end-users. We will also explore the experiences of caregivers and therapists in their role to facilitate end-users to operate the BCI system. No research to our knowledge has explored the perspectives of non-expert caregivers in the set up and support of end-users using BCI at home.

1.4.3 Activity recognition with the TMHSS

Activity monitoring is an increasingly important research area due to the fact that it can be applied to many real-life, human-centric problems, such as elder care and healthcare. Recent studies have shown that physical activities in daily life are an important predictor of risk of hospital readmission and mortality in patients with chronic diseases [53] [54].

Monitoring users' activities allows therapists, caregivers, and relatives to become aware of user context by acquiring heterogeneous data coming from sensors and other sources. Moreover, activity monitoring by inferring user's habits and behavior provides elaborated and smart knowledge and decision support to clinicians, therapists, carers, families, and the patients themselves .

Various methods and tools for subjective and objective habit and activity assessment have already been formulated and developed. Subjective methods, such as diaries, questionnaires and surveys, are inexpensive tools. However, these methods often depend on individual observation and subjective interpretation, which make the assessment results inconsistent [55]. On the other hand, objective techniques use remote monitoring techniques relying on home-automation, wearable and/or environmental sensors [56][57][58]. Several solutions have been proposed for recognizing activities [59], monitoring diet and exercise [60], and detecting changes or anomalies [61]. The work in [62] examines whether a system of basic motion sensors can detect behavioral patterns and adopts a mixture model framework to develop a probabilistic model of behavior. In [63] a Case-driven Ambient Intelligence (AmI) system is proposed (C-AmI), aiming at sensing, predicting, reasoning, and acting in response to the elderly activities of daily living at home. The C-AmI system architecture was developed by synthesizing the output of various sensors, activity recognition, case-based reasoning, along with Elderly in-Home Assistance customized knowledge, within a coherent framework.

One of the primary objectives of our Telemonitoring and Home Support System (TMHSS) which will be described in detail in Section 3.4.3 is to recognize activities and habits of a user who lives alone. Other more complex or abstract kind of knowledge (e.g QoL) will be subsequently inferred from there. Sensor-based telemonitoring systems like our BackHome TMHSS rely on a conjunction of sensors which can range from vital signal devices to sensors which can detect presence in a room or detect a door being opened [64]. Once all of the data have been recorded it is then necessary for data processing to take place to identify if the person requires a form of assistance since an unusual activity has been recognized. Of course, this requires a certain degree of intelligence which should take into consideration the current state of the environment, the performed activity and/or some physiological data [65]. Due to issues regarding personal privacy, technical installations, and costs of technology, the most adopted sensors are anonymous binary sensors [64]. Binary sensors do not have the ability to directly identify people and can only present two possible values as outputs ("0" and "1"). Typical examples of binary sensors deployed within smart environments include pressure mats, door sensors, and movement detectors. This is the case of the TMHSS of the BackHome system which will be implemented and evaluated here.

A number of studies reporting the use of binary and related sensors have been undertaken for the purposes of activity recognition [66]. Nevertheless, sensor data can be considered to be highly dynamic and prone to noise and errors [67]. One of the requirements of our TMHSS is to be cheap and non-intrusive. Therefore we will use a minimum number of wireless binary sensors adapted to the user's home configuration, avoiding camera-based or wearable sensors. Those requirements imply that we will need to cope with errors and noise and to find solutions to overcome those. We will learn that sensors are not 100% reliable: sometimes they miss events or detect the same event several times. When sensors remain with a low battery charge they get worse. Moreover, also gateways and Internet connections may lead to wrong data.

The increasing social demand for intelligent telemonitoring systems makes necessary to put more emphasis in activity recognition methods that deal with environments prone to errors [68]. We will introduce a step forward in this direction by introducing a novel and effective hierarchical approach [69] [70], a discriminative method based on machine learning techniques, aimed at reducing errors from the sensors, which will be integrated in our TMHSS. This approach is aimed at improving the classification accuracy in detecting if a user is at home, away, alone or with some visits, under complex, noisy and unstable environments.

1.4.4 Context-aware QoL telemonitoring

As we will describe in detail in Chapter 2, we are advancing a general methodology to assess QoL using context-aware techniques[10][11][12]. We are defining a Visual Analogic Scale (VAS) QoL questionnaire composed of the following items: MOOD, HEALTH, MOBILITY, SATISFACTION WITH CARE, USUAL ACTIVITIES (which includes SLEEPING), and PAIN/DISCOMFORT. Those items are categorized into two groups: monitorable and inferable. Monitorable items can be directly gathered from sensors without relying on direct input from the user. Inferable items can be assessed by analyzing data retrieved by the system when considering activities performed by the user not directly linked with the sensors.

We will focus on two monitorable items (i.e., MOBILITY and SLEEPING) and one inferable item (i.e., MOOD). In particular, our TMHSS is able to detect and acknowledge the location of the users over time as well as the covered distance in kilometers and the places where they stayed. At the same time, the system detects when the users are sleeping as well as how many times they are waking up during the night. Merging and fusing the information related to MOBILITY and SLEEPING, we will also infer the overall MOOD. The underlying assumption is that mood is related to usual activities performed during the overall day. Thus, we decided to study it as the conjunction of the overall mobility activity as well as the quality of sleep. It is worth noting that it is just an approximation of what mood is and results should show that this simplification can be improved considering other relevant data. In fact, in Chapter 5 we will suggest that future solutions should for instance consider mining social activities (such as mailing, browsing, and social networking) for the MOOD item. Unfortunately, due to the very few amount of social data (also considering that BackHome end-users hardly used social networks on a daily basis) we will decide not to consider this aspect and to leave it as a future work.

The adopted solution is based on the BackHome TMHSS presented in Section 3.4.3 of Chapter 3. Data gathered from the home sensors and outdoor data collected by the smartphone are continuously processed and analyzed through machine learning techniques and suitable classifiers built to recognize the score perceived by the user on the selected QoL item.

Results in section 4.3.4 of Chapter 4 will show that the TMHSS is an easy-to-install sensor-based system that can be used completely separated from the overall BackHome system to monitor activities and habits of people that need assistance (i.e., disabled or elderly people). Preliminary results regarding the ability of the system to assess three items of a quality-of-life questionnaire (namely, mobility, sleeping, and mood) will show that the approach is highly promising. In particular, training it for a longer period of time and with more users, a more effective system should be able to be built able to predict new items belonging to quality of life questionnaires.

1.4.5 Telemonitoring severely disabled people

The TMHSS will be used and evaluated for activity recognition (as introduced in Section 1.4.3) and QoL assessment (as introduced in Section 1.4.4) with able-bodied users and elderly people at home. The TMHSS integrated to the overall BackHome system will eventually be deployed and tested during 6 weeks in real disabled end-users' homes for independent home use.

The final tests will involve deployment of technology at end users' homes, for a continuous collection and analysis of data. As we have already mentioned, the Use Case at hand has the advantage that a severely disabled user needs to rely on assistive technology in order to autonomously undertake most actions and tasks and might recognize sensors as part of the assistive and aiding technology. The main disadvantage, though, will result to be the high cost of equipment, especially BCI, and the uniqueness of the target end user at home, which will only allow to have a limited number of end users in the final experiment.

However, 4 end users will eventually be enrolled: 3 end users provided by Cedar Foundation in Northern Ireland and 1 end user provided by University of Würzburg in Germany will be testing the BackHome system at their own private homes. Out of those 4 end users, only results from 2 of them at Belfast will be completely analyzed, because the other 2 end users are eventually dropping-off the experiments due to personal unmanageable reasons, and are therefore not completing the whole validation process.

Taking into account those limitations, we will manage to carry out continuous evaluation of the TMHSS integrated in the BackHome system and its telemonitoring, activity recognition and QoL assessment features with severe disabled people at their own living environment. Again, the context-aware Quality of Life telemonitoring system is showing promising results but will need future research and development and evaluation work to reach the maturity, reliability and precision required for such an ambitious and human-centric technology.

The researched telemonitoring and assessment tools shall evolve into useful dashboards and decision support systems for therapists, clinicians and caregivers which have the potential to seamlessly impact healthcare and assistance, as will be discussed in Chapter 5 and concluded in Chapter 6.

Chapter 2

Methodology for context-aware Quality of Life assessment

2.1 Introduction

Telemonitoring Quality of Life (QoL) of individuals is one angular basis for current and future telemedicine and teleassistance solutions. In this chapter we are proposing a methodology to assess and telemonitor QoL of individuals based on the awareness of user context. This methodology holds a generic approach to be applied to different eHealth use cases and is based on the acquisition, fusion and processing of heterogeneous data coming from sensors, devices, and user interaction, and the knowledge inferred from the correlation of this processed data and the input coming from proposed questionnaires mapped to standard taxonomies. The proposed methodology is ambitious and future longer term work will necessarily involve broader validation and enhancements with the study of representative user data coming from other applications beyond the BackHome use case which we are addressing here.

To provide an introduction to all the related issues, in next Section 2.2 there is a State-of-art review of relevant work on standardization of health status metrics, QoL assessment, context-aware user profiling, and telemonitoring and home support. Later on, the methodology is presented in Section 2.3, closing with a hint of the methodology in practice in Section 2.4.

2.2 Background

2.2.1 Standardization of health status metrics

Several standard terminologies and classifications exist, which can be used for an interoperable representation of QoL. Some examples are: the Systematized Nomenclature of Medicine Clinical Terms (SNOMED CT); the Unified Medical Language System (UMLS); the International Classification of Diseases version 10 (ICD-10); and the International Classification of Functioning, disability and health (ICF) defined by the WHO. In addition to terminologies and classifications, information models such as the virtual Medical Record (vMR) contribute to solve interoperability problems in the electronic exchange of QoL information.

Several questionnaires are used to evaluate functioning, disability and health. The ICF classifies these concepts, specifies their range of values, and can be used to solve interoperability problems among health institutions that employ different measuring questionnaires. To this aim, questionnaire items can be encoded to ICF concepts following the standardization effort proposed by [71].

Difficulties in mapping clinical questionnaires to standard terminologies and ontologies in the rehabilitation domain (e.g., data from questionnaires having a finer granularity than ICF categories) have been addressed in [72]. ICF core sets are subsets of the ICF that have been created according to specific pathologies or rehabilitation processes. Core sets are useful because, in daily practice, clinicians and other professionals can use only a fraction of the about 1400 categories found in the ICF.

After clearing those difficulties, we recently proposed a methodology to collect, normalize and measure data coming from standardized scales which patients input regularly with the support of caregivers and clinicians [7]. Our methodology provided metrics to assess the evolution of the health status of an individual, compare it with others, and even provide decision support in intervention planning [9]. The purpose of that methodology is to monitor and predict indicators of the health status of individuals and populations, using ICF for automatic standardization and automatic graphical representation of the current and future health status to support prognosis decision support [73].

Furthermore, we used that methodology to provide compared evolution of the health status of an individual in relation to population with similar conditions, for the purpose of patient empowerment in the framework of a social network for people with disabilities of neurological origin, Circles of Health [6]. Figure 2.1 depicts one sample Circles of Health screenshot which presents to the end user of the social network in this case the status of the subcategories of ICF's category Body Function for this user, pointed with a black star, and in the context of a color map which outlines the distribution of the status of the population with similar condition for each ICF subcategory.

Last but not least, we have also employed this methodology to measure and automatically assess socioeconomic impact of health interventions, such as rehabilitation interventions, by comparing health status of individuals and computing costs before and after the intervention[8].

2.2.2 QoL assessment

The World Health Organization Quality of Life (WHOQOL) project [74] has the aim to develop an international, cross-cultural QoL-assessment instrument based on the WHO QoL definition [14]. The WHOQOL instrument was collaboratively developed in a number of centers worldwide, and has been widely field-tested.

In [75], QoL was defined as the value assigned to life duration based on the perception of physical, psychological, and social limitations. According to their view, QoL is related to the reduction in opportunities due to diseases, their sequel, treatment, and to health policies. Otherwise, in [76] QoL is defined as the subjective perception, influenced by the current health status, of the ability to realize activities important for the person.

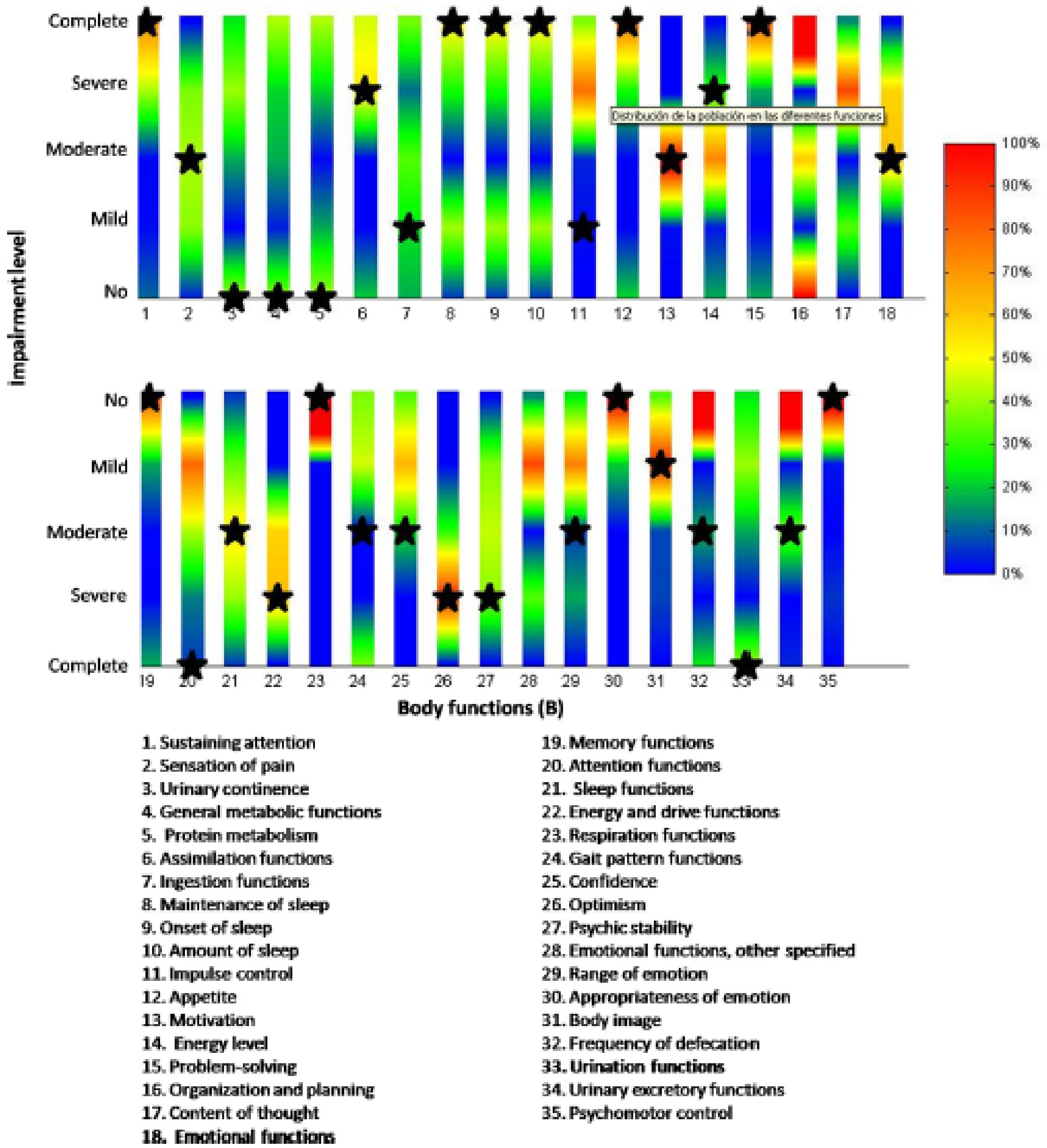

FIGURE 2.1: Graphical representation of the status of individuals in a population context across categories of the ICF (by Circles of Health).

QoL can also be considered as a dynamic and changing concept that includes continuous interactions between the person and the environment. Accordingly, QoL in ill people is related to the interaction among the disease, the patients' character, the changes in their life, the received social support, as well as the period of life in which the disease appears.

Healthcare organizations use several tools to acquire QoL-related information. These tools make use of specific terms, which are sometimes ambiguous: descriptor, grade, item, index, indicator, parameter, questionnaire, scale, score, and test. The terminology used in this paper is part of an ontology (encoded in OWL 2 [77]) which is defined as follows [72]:

- *Indicator*: a (subjective or objective) parameter, category, or descriptor used to measure or compare *activities and participation*, *body functions*, *body structures*, *environment factors*, *processes*, and *results* (e.g., *dressing* or *skull*).
- *Index*: a combination of indicators, questionnaires and possibly other indexes. The function representing this combination gives as summarizing result a *score* (e.g., *Barthel index*).
- *Item*: a single *question* or *concept* (e.g., *Mobility*).
- *Questionnaire* (or *instrument* or *test*): a set of questions (or *items*) answered using a *scale* (e.g., *EQ-5D*).
- *Scale*: a mapping between some ordered (qualitative or quantitative) values (or *grades*) and their description. These values are used to answer questionnaires (e.g., *I have no problems in walking about*, *I have some problems in walking about*, *I am confined to bed*).

Several questionnaires have been proposed and adopted to assess QoL. Let us summarize here the most widely adopted:

- The *WHOQOL-BREF* questionnaire [78] comprises 26 items, which measure the following broad domains: physical health, psychological health, social relationships, and environment.
- The *EQ-5D-5L* questionnaire [79] was developed by the EuroQol Group in order to provide a generic measure of health status. Applicable to a wide range of health conditions and treatments, it provides a simple descriptive profile and a single value for health status that can be used in the clinical and economic evaluation of healthcare as well as in population health surveys.
- The *RAND-36* questionnaire [80] is comprised of 36 items that assess eight health concepts: physical functioning, role limitations caused by physical health problems, role limitations caused by emotional problems, social functioning, emotional well-being, energy/fatigue, pain, and general health perceptions.
- The *Short Form (36) Health Survey* (SF-36v2) [81] is a questionnaire about patient health status and is commonly used in health economics in the quality-adjusted life year calculation to determine the cost-effectiveness of a health treatment. The SF-36 and RAND-36 include the same set of items, however the scoring of general health and pain is different [82].

- The *Barthel* questionnaire [83] is used to measure performance in Activities of Daily Living (ADLs). It uses ten variables describing ADLs and mobility. The higher the score derived from this questionnaire, the greater the likelihood of being able to live at home with independence following discharge from hospital.

2.2.3 Context-awareness

Let us follow the classification of context proposed by [20] which takes into account "five fundamental categories for context information": "Individuality Context", "Location Context", "Activity Context", "Relations context" and "Time Context".

The "Individuality Context" describes the state of the entity itself, offering the information that can be observed about it. This category divides the entities in four different types:

- *Natural Entity Context*: it contains the entities which appear without the human intervention. Include living and inert entities (e.g., atmosphere, water and plants).
- *Human Entity Context*: it refers to all the characteristics of human beings (e.g., user's preferences about language, input device and colour schemes).
- *Artificial Entity Context*: as opposite of the *Natural Entity Context*, it includes all the elements developed or built by humans (e.g., buildings, ambient sensors and smart home devices).
- *Group Entity Context*: it is a collection of entities that share common characteristics or have some relationship (e.g., a group of people with the same disorder, as "Acquired Brain Injury", or a group of relatives, as "My Family").

The "Location Context" includes the information related to the position of the entity. It involves the global or relative position among entities, independently from the technique used to position them. For instance, user's home can be used as spatial information or a coordinated system can be used. Moreover, this information can be related to a non-physical position like IP address which is a position a smart home device connected to computer network.

"Activity Context" covers the activities in which the entity is, was and will be involved and can be described, for instance, as tasks, aims, and actions.

The "Relations Context" describes the relations among different entities of a context-aware system, such as human beings or things. This information can be classified into three kinds of relations: "Social Relations", "Functional Relations", and "Compositional Relations".

Finally, the last category is "Time Context". In fact, the features of context can be usually evaluated or have variations from one temporal point to other. It means that they have a temporal dimension which should be considered as a key information for the context [84].

Other classification approaches of context specific to healthcare applications have been proposed in the literature. In [85], the following categories have been considered:

- "User information", which contains knowledge on habits, emotional state, and physiological conditions. This category matches with the "Human Entity Context" proposed in [20].
- "User's activities", which includes spontaneous activities, engaged tasks, or idle state. It is quite similar to the "Activity Context".
- "Location", which includes global and relative position, directly matches with "Location Context".
- "Physical conditions", which contains luminosity, pressure, heart rate, and temperature, for example. It also corresponds to the "Human Entity Context".

We have discarded this last approach because it does not take into account the "Relation Context" information and does not explicitly include the "Time Context".

In [86], authors stress the difference between context model and user model by the way of obtaining the data. On the one hand, they state that the user model is related to data acquired thought the interactions of the user with the application. On the other hand, the context model is obtained mainly from sensors. Especially this last issue is in contradiction from the view of choice. In fact, we are considering context as a complete set of information that may come from sensors as well as from interactions and/or relations with other entities involved in the same context-aware system.

2.2.4 Telemonitoring and Home Support

Home sensor technology may create a new opportunity to reduce costs by helping people stay healthy and in their homes longer as they age. An interest has therefore emerged in using home sensors for health promotion [87]. One way to do this is by Telemonitoring and Home Support Systems (TMHSSs). TMHSSs are aimed at remotely monitoring patients who are not located in the same place of the healthcare provider. The support of TMHSSs allow patients to be maintained in their home [88]. Better follow-up of patients is a convenient way for them to avoid traveling and to carry out some of the most basic healthcare tasks by themselves, thus reducing the corresponding overall costs [89] [90].

Summarizing, a TMHSS allows:

- To improve the quality of clinical services, by facilitating the access to them, helping to break geographical barriers.
- To keep the focus in a patient centered assistance, facilitating the communication between different clinical levels.
- To extend the therapeutic processes beyond the hospital, like patient's home.
- To save unnecessary costs and to achieve a better costs/benefits ratio.

In the literature, several TMHSSs have been proposed. Among others, let us recall here the works proposed in [91], [92], and [93]. The system proposed in [91] provides users personalized healthcare services through ambient intelligence (AmI). That system is responsible of collecting relevant information about the environment. An enhancement of the monitoring capabilities is achieved by adding portable measurement devices worn by the user thus vital data is also collected out of home.

A TMHSS is proposed in [92] which aims at improving healthcare and assistance to dependent people at their homes. That system is based on a Service-oriented Architecture (SoA) model for integrating heterogeneous wearable sensor networks into ambient intelligence systems. The adopted model provides a flexible distribution of resources and facilitates the inclusion of new functionalities in highly dynamic environments. Sensor networks provide an infrastructure capable of supporting the distributed communication needed in the dependency scenario, increasing mobility, flexibility, and efficiency, since resources can be accessed regardless their physical location. Biomedical sensors allow the system to continuously acquire data about the vital signs of the patient.

In [93] ContextProvider is proposed, which is a framework that offers a unified, query-able interface to contextual data on the device. In particular, it offers interactive user feedback, self-adaptive sensor polling, and minimal reliance on third-party infrastructure. It also allows for rapid development of new context and bio-aware applications.

When targeting BCI users, some work has been presented to provide smart home control [94] [95] [96] [97]. To our best knowledge, TMHSSs have not been integrated yet with BCI systems beyond opening ways to allow remote communication between therapists and users [98].

2.3 Methodology for context-aware Quality of Life assessment

Next we will present the general methodology to assess QoL by relying on context-aware techniques. We have implemented this proposed methodology in the TMHSS of the BackHome system. Nothing prevents to adapt it in a more general way to other use cases, e.g. remotely monitored chronic patients in an integrate care scenario. In fact, target beneficiaries of such methodology will be the elderly, the disabled, and complex chronic patients.

We have introduced the underlying idea of the proposed methodology and the details in [99] and have developed further in [12], [10] and [11]. To our best knowledge it is the first attempt to adopt context-aware techniques to assess QoL.

2.3.1 The proposed telemonitoring system

To monitor the QoL of disabled people, we propose a sensor-based Telemonitoring and Home Support System (TMHSS) integrated to the BackHome system aimed at helping the user to be more independent by providing smart home control. It also provides eInclusion capabilities thanks to the possibility to carry out Web browsing, use e-mail services, as well as interact with the most popular social networks.

Our sensor-based BackHome TMHSS is able to monitor the evolution of the user's daily life activity at home, once discharged from the hospital [100], providing QoL automated assessment based on information gathering and data mining techniques [101]. Specifically, wearable sensors allow to monitor fatigue, spasticity, stress, and further user's conditions. Environmental sensors are used to monitor –for instance– temperature and humidity, as well as the movements and the physical position of the user (through presence/motion sensors). Smart home devices enable physical autonomy of the users and help them carry out daily life activities. From the social perspective, an Internet-connected device allows the user to communicate with remote therapists, careers, relatives, and friends through Skype, email, or social networks (i.e., Facebook and Twitter).

The proposed sensor-based system has the potential of acquiring personalized information through data coming from: (i) a BNCI system[1] that allows monitoring ElectroEncephaloGram (EEG), ElectroOculoGram (EOG), and ElectroMyoGram (EMG) signals; (ii) wearable, physiological, and biometric sensors, such as ElectroCardioGram (ECG) sensor, heart-rate sensor, respiration-rate sensor, Galvanic Skin Response (GSR) sensor, EMG switches, and inertial sensors (e.g., accelerometer, gyrocompass, and magnetometer); (iii) environmental sensors (i.e. gas, smoke, luminosity, humidity, and temperature sensors); (iv) smart home devices (e.g., home lights and TV); and (v) devices that allow interaction activities (i.e., a desktop PC).

2.3.2 QoL features

Starting from the standard questionnaires encountered in the literature, we are proposing a new Visual Analogue Scale (VAS) QoL questionnaire (see Figure 2.2). The proposed questionnaire is based on the standard EQ-5D-5L questionnaire and is designed to assess the key QoL features of an individual, which correspond with the main features that BackHome's TMHSS aims to monitor. In other words, we consider the user's QoL as the conjunction of the following items: *Mood*, *Health Status*, *Mobility*, *Self-care*, *Usual Activities*, and *Pain/Discomfort*. According to [102], Table 2.1 shows the translation of the selected questionnaire into the ICF categories.

2.3.3 Context and QoL

Studying the different items that compose off-the-shelf QoL questionnaires as –for instance– the one presented in the previous subsection, some similarities with the concept of "context" can be noted. To highlight these similarities, let us consider the follow classification of QoL items:

- *User Information*, information related to physical and mental health (e.g, *mood* and *pain*).
- *Interactions*, environmental interaction (e.g., *control over home environment*) and social relationships (e.g., *face-to-face communication* and *telecommunication*).
- *Location*, information related to user's position as well as her/his movements (e.g., *mobility*).
- *Daily activities*, activities performed by the user (e.g., *leisure activities*).

[1] Currently, the EEG-P300-2D, a standard P300 control paradigm.

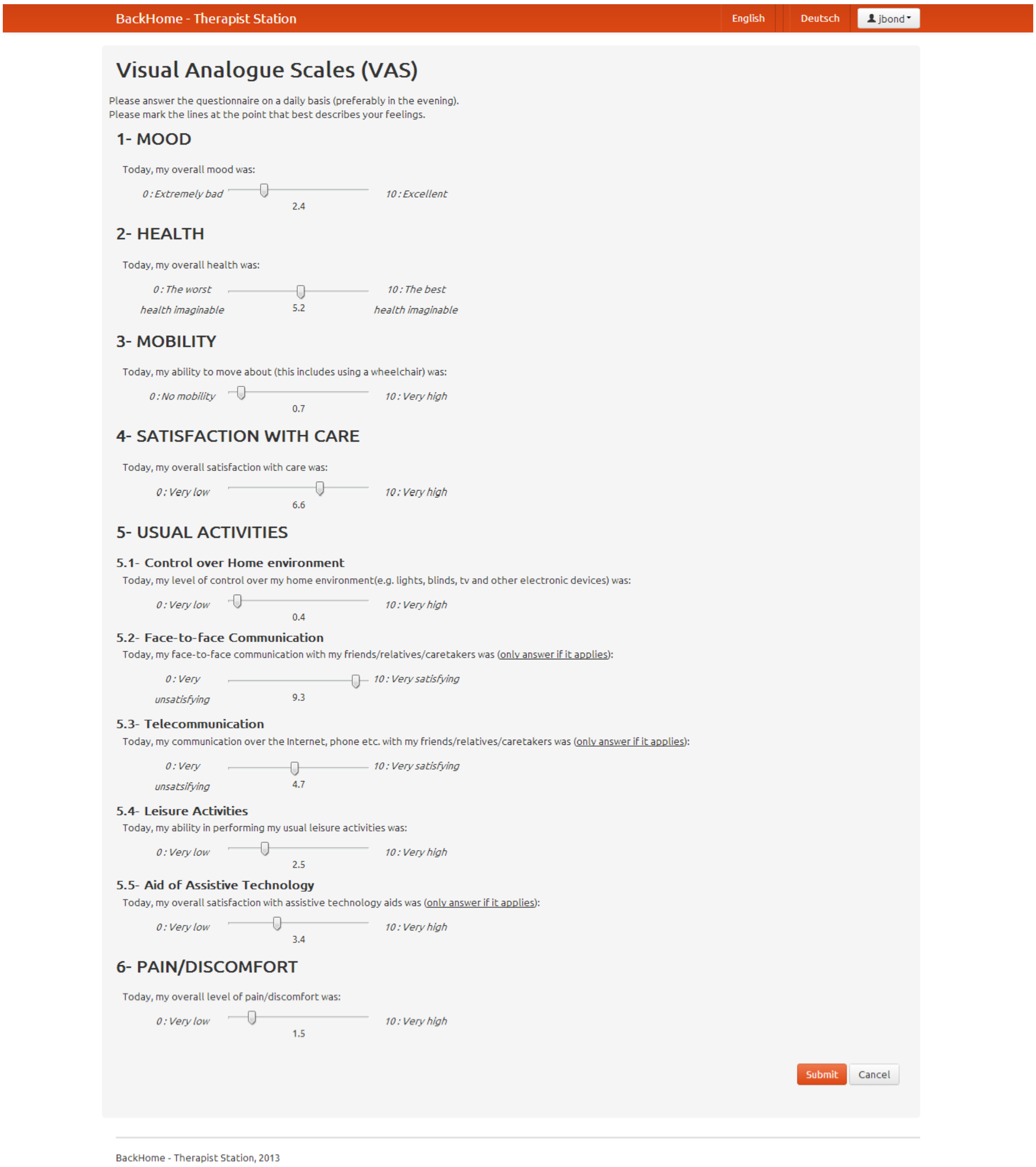

FIGURE 2.2: The BackHome VAS QoL questionnaire.

TABLE 2.1: The translation of items of the adopted VAS questionnaire into ICF categories.

Questionnaire item	**ICF Category**
Mood	b152 - emotional functions
Health Status	b130 - energy and drive functions b134 - sleep functions b730 - muscle power functions b735 - muscle tone functions b760 - control of voluntary movement functions
Mobility	d4 - mobility d450 - walking d498 - mobility, other specified
Self-care	d5 - self-care d510 - washing oneself d540 - toileting d540 - dressing
Usual Activities	d6409 - doing housework, unspecified d7609 - family relationships, unspecified d839 - education, other specified and unspecified d8509 - remunerative employment, unspecified d9209 - recreation and leisure, unspecified
Pain/Discomfort	b152 - emotional functions b280 - sensation of pain b289 - sensation of pain, other specified and unspecified

Although not explicitly shown, *time* is also an important item when compiling a questionnaire. In fact, it usually impacts the perception of the users' environmental factors influencing their status and, thus, the overall QoL. For instance, *mood* usually changes depending on the hour of the day, the season, and the number of sleeping hours.

It is easy to note that the classification given above matches very well with the definition of "context", given in [20] and recalled in section 2.2.3. Thus, starting from that definition, let us classify the QoL items according to the "five fundamental categories for context information":

- *Individuality*, it describes the state of the entity. In QoL, being the entity the individual, *Individuality* corresponds to the *User Information* category.
- *Relations*, it describes the relations among different entities of a context-aware system. In QoL, it can be viewed as relations among entities (e.g., users), as well as "external" entities (e.g., caregivers and relatives). In a more broad view, it could also consider interaction with the environment. In other words, *Relations* corresponds to the *Interactions* category of the previous classification.
- *Location*, it describes the position of an entity. In QoL, it is translated into the position of the individuals and their ability to move around.

- *Activity*, it describes the activity corresponding to an entity in a context-aware scenario. In QoL, it covers all the daily life activities performed by the individual. Thus, it corresponds to the *Daily Activities* category.

- *Time*, it describes the temporal dimension of the gathered information and it is really important in the classification of context [84]. In the case of QoL, "time" not only affects the context status of the individuals' surroundings, it also influences their physical status (e.g., the same fatigue value associated to daily activities has a different impact depending on the time in which it is gathered). As already said, *Time* does not have a direct correspondence with the QoL items. On the other hand, it can be considered as a "transversal" category that affects all the others.

The correspondence between context and QoL assessment allows us to study how to automatically assess QoL by relying on context-aware techniques. In fact, those techniques have been proposed and used for recognizing activities and behavioral patterns [62] [103] or monitoring diet and exercise [60]. Similarly, we claim that context-aware techniques can be adopted to automatically assess QoL of individuals.

Keeping in mind the above classifications, we can then identify all the sensors involved in the process of gathering data to assess QoL, taking the BackHome Use Case into account:

- *Individuality*
  - the BNCI system, which allows monitoring EEG, EOG, and EMG signals;
  - wearable, physiological, and biometric sensors, such as ECG sensor, heart-rate sensor, respiration-rate sensor, GSR sensor, EMG switches, and inertial sensors (e.g., accelerometer, gyrocompass, and magnetometer).

- *Relations*
  - social networking (i.e., through Facebook and Twitter)
  - communications to the therapists (i.e., through the telemedicine platform).

- *Location*
  - environmental sensors (e.g., temperature and humidity sensors);
  - inertial, location, and motion sensors.

- *Activity*
  - smart home devices (e.g., wheelchairs, lights, TVs, doors, windows and shutters);
  - devices that allow interaction activities (e.g., a desktop PC);
  - devices to perform rehabilitation tasks (e.g., a robot).

Figure 2.3 shows the complete set of information available highlighting the category to which each input belongs to: *pentagons* correspond to *Individuality*; *rectangles* to *Relations*; *hexagons* concern with *Location*; and *circles* with *Activity*.

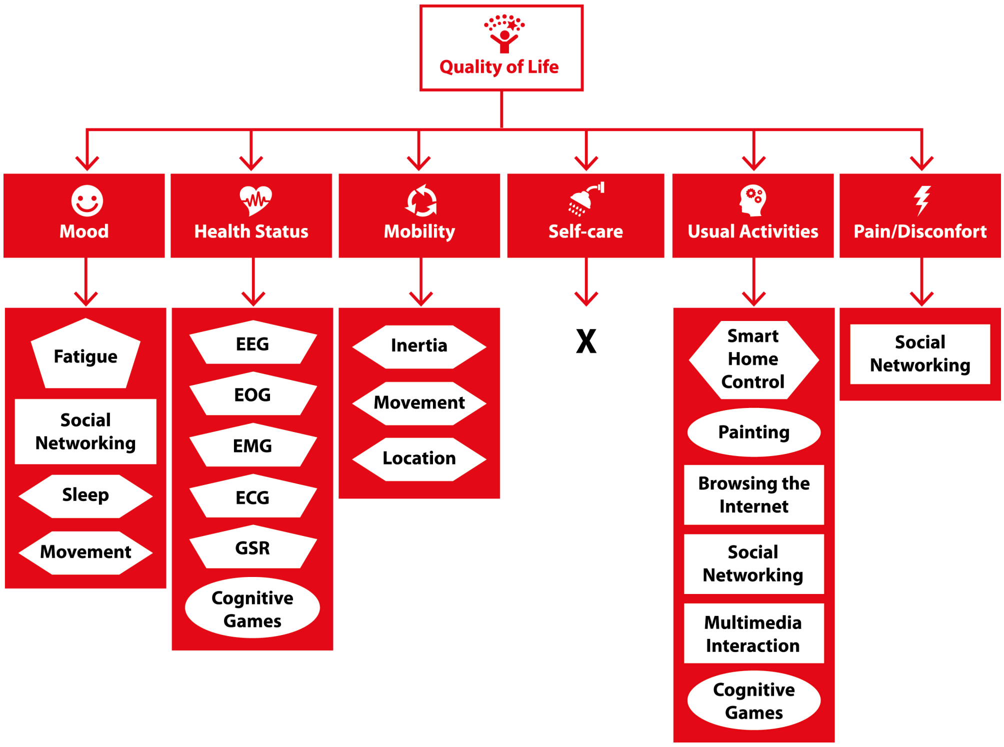

FIGURE 2.3: Data collected with the BackHome TMHSS and their relationship with the proposed QoL categories.

2.3.4 The approach

Personalized information is collected through the combination of data coming from the sensor-based system. This information is fused with data gathered when the user is interacting with the BackHome system and answering questionnaires, if needed. All that data is used to inform the system about users' behaviors, social autonomy, QoL, etc. and to feed other decision support tasks. In particular, two kinds of data are considered: *monitorable* and *inferable*. Monitorable data can be gathered from the wearable, home automation, and environmental sensors, as well as from the BNCI system (i.e., without relying on direct input from the user). For example, this kind of data provides the answer to the item on "Mobility" (*Today, my ability to move about was...*). On the other hand, all data inferred by analyzing data retrieved by the system (e.g., by considering activities performed by the user while interacting with a social network) belong to the latter category. This kind of data allows, for instance, answering the item on "Mood" (*Today, my overall mood was...*).

Let us note that this does not imply that monitorable and inferable data are mandatorily monitored or inferred. In particular, in the evaluation of the BackHome system we are deciding not to monitor nor infer some data (such as, those related to *Self-care*), due to privacy issues. Moreover, users can decide to switch off the monitoring of any descriptor.

In the following, we briefly describe how each monitored data can be gathered to assess the items of the given questionnaire.

Monitorable data

Health Status: Through the adoption of wearable, physiological, and biometric sensors, the system is able to monitor improvement and/or worsening of the health status of the user.

Mobility: Through the adoption of environmental location sensors, the system is able to know the position of the user, time after time. It is worth pointing out that, in BackHome, users are typically on a wheelchair, thus the walking activity is not of interest here. To detect the position of the wheelchair and its movements, RFID tags could be embedded into the wheelchair together with the other environmental sensors.

Usual Activities: Being human-computer-interaction made through a BCI system, it is possible to monitor all the activities performed by the user on the PC and while interacting with smart home control and communication devices. In other words, the system is able, through the BCI system, to know which action is performed, such as home environment interactions, face-to-face communications, telecommunications, and leisure activities. Moreover, the activities performed on further devices in the Internet of Things that allow some kind of interaction and stimulation activities (e.g., devices to play, listen to music, enjoy painting activities or other leisure activities) may be stored to study user's interaction and usual activities.

Inferable data

Mobility: We have seen how environmental location sensors are used to directly monitor the position of the user time after time. However, we infer more abstract mobility information of the user from virtual sensors, i.e. the information extracted from the combination of data of different direct sensors and the application of machine learning techniques. For instance, we will see in next chapter how we infer whether the user is at home or away fusing data from the door sensor and motion sensors. Similarly, we are also inferring other mobility parameters such as the level of activity.

Mood: Changes observed in habits of daily life activities can be studied to assess the mood. The degree of overall satisfaction can be also inferred by analyzing data on fatigue, spasticity, stress, and other user's conditions retrieved by the BCI system and other wearable sensors. Moreover, analogously to pain and discomfort, anxiety and depression can be inferred by the system by adopting suitable text mining algorithms on the performed social activities. We are now inferring Mood from the level of activity and quality of sleep, although we know this is a reductionist approach.

Usual Activities: End-users can interact with their family and friends through the support of a communication system (e.g., Skype) or social network (e.g., Facebook and Twitter). Thus, suitable text mining algorithms can be adopted to infer the family and friend relationships.

Pain/Discomfort: Text mining algorithms, applied to social networking and communication activities, might be adopted to assess the degree of pain or discomfort. Of course, privacy and technological considerations should be taken into account to define the scope of those analyses.

2.4 Methodology in practice

Information gathered by sensors is used as classification features to build a multi-class supervised classifier; one for each user and for each item of the questionnaire we are interested to answer to. As a first approach in order to study the feasibility of the

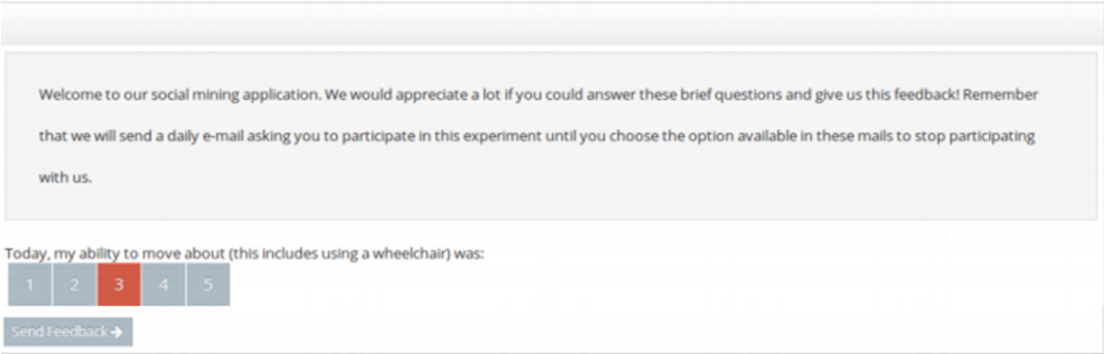

FIGURE 2.4: The question the user is asked to answer on a daily basis.

methodology in practice, as a proof of concept we focused on how to assess movement capabilities, i.e., the item "Mobility" of the QoL questionnaire. In other words, we intended to answer to the question "Today, how was your ability to move about?".

The proposed approach considers the following features: (i) time spent on bed and (ii) maximum number of continuous hours on bed, extracted from the bed sensor; (iii) time spent on the wheelchair and (iv) maximum number of continuous hours on the wheelchair, extracted from the seat sensor; (v) time spent in each room and (vi) percentage of time in each room, extracted from the motion sensor; (vii) room in which most time is spent, inferred by a virtual sensor; (viii) total time spent at home, extracted from the door sensor; (ix) total time spent watching TV and (x) total time spent using computers, extracted from the corresponding power meters and switches; (xi) number of kilometers covered by transportation means, (xii) number of kilometers covered by moving outdoors on the wheelchair and (xiii) number of visited places.

To train and test the classifier, the user is everyday asked to answer to the question "Today, how was your ability to move about?"(see Figure 2.4). User's answer is an integer number in a scale from 1 to 5 that corresponds to users' satisfaction in their movement ability. User's answers are then used to label the entries of the dataset for the purpose of training and testing, into three categories: "Low" (1-2), "Normal" (3) and "High" (4-5).

In order to study the feasibility of the approach, we carried out a proof of concept with one able-bodied user living alone[104]. We considered a window of three months and made comparisons of results for three classifiers: decision tree, k-NN with k=1, and k-NN with k=3. During all the period, the user answered to the question "Today, how was your ability to move about?", daily at 7 PM. Answers were then used to label the item of the dataset to train and test the classifiers built to verify the feasibility of the proposed QoL approach. Given a category (i.e., "Low", "Normal" and "High"), we consider as true positive (true negative), any entry evaluated as positive (negative) by the classifier that corresponds to an entry labeled by the user as belonging (not belonging) to that class. Seemly, we consider as false positive (false negative), any entry evaluated as positive (negative) by the classifier that corresponds to an entry labeled by the user as not belonging (belonging) to that class. Results were then calculated in terms of precision, recall, and F1 measure. The best results were obtained using a decision tree. In fact, in that case, on average we calculated a precision of 0.64, a recall of 0.69 and a F1 of 0.66. It is worth noting that, as expected (the user is healthy and does not have difficulty in movements), the best results were obtained in recognizing "Normal" mobility. In fact, in this case we obtained a precision of 0.80, a recall of 0.89 and an F1 measure of 0.84.

This proof of concept confirmed the potential of the proposed methodology, which will be evaluated in Chapter 4 and discussed in Chapter 5.

Chapter 3

The BackHome use case: A User Centered Design approach

3.1 Introduction

In the roadmap towards 2020 for BCI research we proposed in [105][106], applications are targeted at replacing, restoring or improving the functions of people with some degree of disability as a key objective of future BCI research and innovation. Additionally, BCI use by able-bodied users for enhancing their functions or for broadening their leisure activities are expected to gain momentum and drive research.

The progress of BCI research within those "replace" and "restore" scenarios aim to deliver BCI-based products that represent an alternative to current Assistive Technologies (AT). Additionally, the progress of BCI research within the "improve" scenario will deliver new rehabilitation methods and tools. With BackHome we have promoted these trends with the ambition to move BCI systems from laboratories and controlled environments into the home of people for their independent use [69]. This requires a system that is easy to set up, portable, and intuitive.

In this Chapter we are presenting the User Centered Design (UCD) process employed to research and develop a multifunctional BCI system [52], including the collection of user requirements, the iterative development process together with the analysis of test results and feedback recommendation from able-bodied and disabled end users. Last but not least, the Chapter presents the outcome of this UCD process, which is the final BackHome system that we have installed in target end users' homes for final testing and evaluation.

Driven by this UCD approach towards independent home use, in BackHome we developed and refined five key innovations advancing current state of art: (i) a modular and distributed architecture able to meet the requirements of a multi-functional BCI with remote home support (see Figure 3.5 below); (ii) BCI equipment with practical electrodes aimed at setting a new standard of lightness, autonomy, comfort and reliability; (iii) easy-to-use software tailored to people's needs to manage a complete range of multifunctional applications finely tuned for one-click command and adaptive usage; (iv) a telemonitoring and home support system to remotely monitor and assist BCI independent use; and (v) a Web-based application for therapists, which offers remote services to plan and monitor BCI-based cognitive rehabilitation and pervasively assess the use of the system and the quality of life of the individual[52][107].

3.2 Background

Until recently, BCI research focused primarily on validating devices with healthy volunteers in laboratory settings. This has begun to change [38][108][109]. These efforts have shown that BCIs can provide solutions for people in their homes[110][98]. However, efforts to provide BCI solutions for home usage have highlighted one major problem: dependence on outside support. Thus, the key problems issued with BCI systems at home – and also the two principal reasons why home users need support – are difficult electrode set-up and need of software support[111]. In [112] it is shown that users do indeed identify electrodes as the top problem for home support and that improved software that integrates varied functionalities without too much problems is also essential[113]. In the following subsections, we briefly summarise the main previous work on practical electrodes, easy to use software, and telemonitoring and home support for independent home use of BCIs.

3.2.1 Practical electrodes

To advance existing BCI systems into a more practical solution for home use it is necessary to improve the hard- and software of existing BCI systems. Since the majority of BCIs are based on electroencephalography (EEG) it is one of the main objectives to improve the sensors, namely the EEG electrodes, which capture brain activity. One of the biggest problems with most non-invasive BCI systems is the need for sensors that rely on electrode gel. Surveys of able-bodied and disabled users [112][114] reveal that users dislike conventional gel-based systems and their associated preparation time and inconvenience. Several different types of electrode systems are available on the market, additionally many research groups tried to improve specific aspects to improve the applicability of the electrodes [115][116][117] or wireless signal transmission. There is room for improvement of user acceptance of BCI equipment by advancing ergonomics of caps, using reliable dry electrodes, wireless light amplifiers, and enable short and easy set up. We have taken into account all these features.

3.2.2 BCI software

Software currently adopted for research on BCI offers the researchers many options and functionalities[118]. Nevertheless, they are very hard to be used from non-experts people. Thus, UCD principles have to been applied to optimize the system around how users can use the system in contrast to force the users to change their behavior to be able to use the system. The UCD is standardized in the ISO 9241-210 [119].

Three main aspects have to be considered to assess the usability of a BCI system: (i) the effectiveness, (ii) the efficiency, and (iii) the satisfaction of the user with the system. The effectiveness is indicated by the accuracy of the BCI system (correct selections of total selections). Accuracies lower than 70% are not acceptable for BCI systems [28]. The efficiency is mainly assessed with the Information Transfer Rate (ITR) [120]. In addition to the accuracy, the ITR includes the information content within each selection (amount of possible selections) and the time needed per selection. Different questionnaires are used to determine the satisfaction of the user with a system. For example, an extension of the QUEST 2.0 [121] for BCI usage was presented in [112]. This is a powerful tool to get feedback from the users about their satisfaction with the BCI system. Another simple method is to let the users fill out a visual analogue scale (VAS) about satisfaction. According to the UCD, the users' feedback is used to improve the current version of the software or to develop a new, better version. Consequently, using UCD principles make the BCI software easier to use, and therefore, more accepted by the target users.

3.2.3 Telemonitoring and home support

Home sensor technology may create a new opportunity to reduce healthcare costs by helping people to stay healthy longer as they age. An interest has therefore emerged in using home sensors for health promotion [87]. This interest has resulted in research and development of Telemonitoring and Home Support Systems (TMHSSs), which are aimed at remotely monitoring patients who are not located in the same place as the health care provider. Those support systems allow users (e.g. the elderly, the disabled or chronic patients) to remain living at their own home [88] keeping (or returning to) their life roles and daily life activities. Continuous monitoring and follow-up of patients is a convenient way for patients to avoid travelling to a health care institution and to perform some of the healthcare tasks by themselves, thus reducing the overall costs of healthcare [89][90]. TMHSS support care providers in the task of being aware of the status of their patients. In particular, for disabled people, telemonitoring enables care providers to get feedback consisting of health status parameters which provide a measure of an individual's QoL and level of disability and dependence; taking into account not only functional and cognitive factors, but also psychological, social, and participation ones. As a consequence, care providers benefit from telemonitoring because preventive and proactive actions can be triggered while clinicians, therapists and caregivers are getting smarter and more precise data. More interestingly, the end users/patients become empowered and their QoL improved.

In summary, a TMHSS allows: (i) to improve the quality of clinical services, by facilitating the access to them, helping to break geographical barriers; (ii) to keep the objective of a patient-centered assistance, facilitating the communication between different clinical levels; (iii) to extend the therapeutic processes beyond hospitals or primary care centers, like at patient's home; as well as (iv) to save unnecessary costs and to achieve a better costs/benefits ratio.

In the literature, several TMHSSs have been proposed [91][92][93]. As targeted for BCI users, some work has been presented to provide smart home control [95][122][94][97]. Nevertheless, to our best knowledge, telemonitoring and home support has not been integrated yet with remote BCI systems as a way to allow remote communication between therapists and users and to improve remote support [98].

3.3 The User Centered Design approach

User Centered Design (UCD) is a process of engagement with target end users that adopts a range of methods to place those who may benefit most from the technology at the center of the design process in terms of development and evaluation. Thus, the system development is iterative and incremental to trigger reflections and get feedback from users, their families, caregivers and therapists prior to implementation of the final system [43]. We have adopted a UCD approach at each phase of the system definition

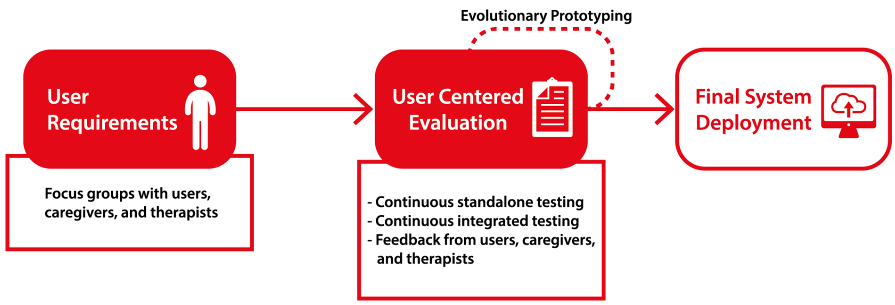

FIGURE 3.1: The adopted user centered design (UCD) approach.

and implementation in order to take into account users' feedback to have a solution that reflects users' requirements, needs and preferences.

Figure 3.1 sketches the adopted approach, which consists of three main steps: (1) first, user requirements have been gathered through focus groups with end-users, caregivers and therapists; (2) then, users' evaluation has been collected to improve the system according to an evolutionary prototyping approach that takes into account continuous feedback from standalone and integrated testing [123] [124]; and (3) finally, the final system has been deployed.

3.3.1 Ethical issues

UCD is important to gather the preferences of target end users in the design and development of emerging technologies. The novelty within this approach is successfully gaining ethical approval to work directly with target end users i.e. people with disabilities of neurological origin, for instance people who have acquired brain injury. The challenges are many to engage in such innovative research with people who are considered to be more vulnerable than the general population. Achieving this helps align technical innovation to end user needs, increasing the likelihood of adoption and sustained use. The very fact that the technology is in the design and evolving phase brings a host of ethical issues to consider, which may be more crystallized when the target end users are considered to have cognitive impairment. An ethical framework developed within the whole UCD process created a robust structure to unpin the research approach.

The core ethical principles of autonomy, beneficence, non-maleficence and justice were kept central to this framework. European legislation, international conventions and local ethics committees were also incorporated. The Ulster University ethics Committee provided ethical approval.

The selection of appropriate end users was important within the ethical framework developed. People with neurological conditions including Acquired Brain Injury (ABI) and Amyotrophic Lateral Sclerosis (ALS) are considered vulnerable groups and it is imperative to safeguard their wellbeing. It is important that potential end users have a thorough understanding of the device and what it can actually do rather than what can be perceived as a result of film or the media. Additionally, informed consent is central to the ethical framework. Key workers within the end user organisations were contacted and asked to make the first contact with potential participants to identify those interested. Next an initial meeting was undertaken to introduce the potential participants to the technology, watch videos of BCI and ask questions before they were given an information leaflet to consider. A cooling off period of one week was given before the potential participants were contacted to assess their interest and desire to participate and give consent. Once the consent form was signed participants were invited to an interview to identify if the participant met the inclusion criteria. It was highly probable as we were recruiting participants for home-based evaluation that not all participants would be able to give verbal or written consent. We would incorporate a number of measures to try to establish consent in this instant and also had to consult with the family and key caregivers when seeking consent from this target participant group.

Maintaining realistic expectations was essential. Recent media attention around BCI technologies has portrayed the systems as a life changing assistive device [125]. However, BCI is not currently an off the shelf solution or a cure for a person with very limited mobility [126]. It is important to keep the perception of the systems functionally at an achievable level in line with the current constraints. Since this technology is not going to be a potential solution for everyone this can lead to feelings of frustration and disappointment. The system can be equally frustrating when it fails to respond to the user as accurately and quickly as they would like. Importantly, end users, family members and caregivers must also be informed that participants will only have access to the BCI during their involvement in the UCD process. This can become challenging if the technology provides a real improvement in a person communication and quality of life.

3.3.2 User requirements

We collected the user requirements that emerged from focus groups with potential target end users, family members, caregivers and therapists and from prior studies involving users of AT in general and BCIs in particular. We then created a prioritised list that contains the requirements in order of importance for the prototypes (see Figure 3.2).

We assigned effectiveness the highest priority, which goes hand in hand with functionality. The user should be able to achieve the desired task with satisfactory accuracy from the system and this is a prerequisite for its usability. Further, the system stability is of utmost importance for independent home use and has been critical during the UCD testing phases. Since the need of the user to request software support should be kept at a minimum, only those applications that have run stable during previous testing phases will be deployed and tested in the final independent home use testing. A key theme that emerged during the focus groups and evaluation phase and has become a crucial objective is to improve the ease of use of the BackHome system. For this matter, both the end user interface that is used to control the applications and the caregiver interface used to launch the system need to be simple enough to be operated without requiring much training. Also the BCI hardware needs to be easy to set up. In order to assure that the main caregiver user interface will be easier to operate, mockups were evaluated by BCI experts and healthcare professionals. The goal was to have a “one-click interface” once the initial setup is done and the caregivers have been trained. Regarding the BCI hardware, during the focus groups phase users criticized

Priority	Key-aspects of the system	User requirements	Recommendations/Planned System Specs
HIGHEST	**Effectiveness**	▪ with the system users should achieve the task as accurately and completely as possible	▪ Implementation of famous faces paradigm for the P300 matrix, dynamic stopping method and error suppression
	Reliability	▪ the system must be stable during everyday use	▪ only those services that are stable (after an initial test with preliminary test users) will be evaluated during independent home use/ software bugs will be fixed during initial testing phase
	Robustness	▪ the system has to be robust with respect to anomalies, malfunctioning or in case some sensors or services stop working; in all those situations, the system should continue to work with reduced functionalities	
	Functionality	▪ the system should allow the user to perform as many (simple) tasks as possible to increase autonomy of user	▪ Spelling, Web browser, multimedia player, cognitive rehabilitation games, smart home control, Brain Painting
	Ease of use	▪ the system should be simple to operate (menus should be intuitive) ▪ the software and hardware must be easy to set-up by non-experts ▪ instructions on how to operate the system must be clear ▪ minimal technical support should be necessary (technical problems should be resolvable via remote access)	▪ assured through the evaluation of a mockup of the software ▪ a one click interface is planned ▪ an easy to understand user guide will be created/ including video explanations
	Efficiency	▪ workload and speed of communication should be at an acceptable level, ideally comparable or better than the AT in use	▪ A dynamic stopping method during usage of the services will assure that only the necessary amount of repetitions will be used to maximize speed
	Safety	▪ the system must not constitute a risk to the health of the user - this concerns especially the safety of the individual parts (electrodes, wires etc.)	▪ the system does not constitute a risk to the health of the user - the hardware is CE certified / this will be communicated to increase its acceptance
	Comfort	▪ The EEG cap should be comfortable to wear for several hours ▪ to prevent fatigue of one modality (e.g eyestrain) users should be able to switch between different control signals (modes of control) ▪ ideally no gel is necessary to acquire good EEG signals	▪ only P300 will be implemented because this control signal offers the best compromise of accuracy and stability ▪ the developed EEG systems can be dry or gel-based depending on the users preferences
	Privacy	▪ no information should be transmitted or be visible to persons except to those it is intended for or the user has agreed to share the information with ▪ information that is transmitted wirelessly or via an internet connection must be transmitted and stored sufficiently securely	▪ A secure protocol will be used for transmission of data over the internet (Hypertext Transfer Protocol Secure, HTTPS) ▪ no sensitive data will be transmitted wireless ▪ All information will be stored according to Data protection laws
	Mobility	▪ to allow for maximum mobility, the system should be small and wireless ▪ it should be possible to use the system in a lying position and/or if the user is seated (e.g. if the user is lying in his bed or sitting in a wheelchair)	▪ the EEG system will be both small and wirelessly
	Possibility of independent use	▪ the user should be able to operate the system with as little help from the caregiver as possible	▪ after the EEG setup is done and the system started, the user can switch between applications or pause the system by himself and because of the planned non-control state detection system, the BCI will refrain from making selections if the user is not concentrating on the control matrix
	Aesthetic design	▪ the design of the interface should be appealing ▪ the design of the cap should be appealing and as inconspicuous as possible	▪ the design of the cap could not be influenced without compromising its functionality ▪ size of the amplifier must be reduced and transmission to the computer is wireless
	Configurable to the needs of the user	▪ the system should contain the possibility to adjust the system to the needs of the individual user (e.g. store pre-recorded sentences or implement shortcuts)	▪ the system will cover many services already but the software will also be implemented such that it allows for extensibility with other applications that are desired by the user

FIGURE 3.2: Recommendations from users in order of priority

the aesthetic appearance of the electrode cap as well as the limited mobility of the system. Users were, however, not involved in the aesthetic design of the cap, since good signal quality and thus effectiveness has a higher priority than the visual appearance. The dry electrodes should help to further reduce the time-needed for the setup of the system. For both the hard- and software setup the recommendation was to create an easy to understand user guide including a FAQ Section explaining the solutions to the most common problems and a video that explains the setup of the system visually.

Of course safety and privacy concerns that were raised during the discussions are of importance, but we did not list them on top of the priority list, because the necessary measures were already undertaken to assure both. Regarding the safety of the system, the EEG hardware needs to be certified as a medical device. Nevertheless precautions will be taken during testing with end users, for instance no person suffering from epilepsy should use the system because of the fast flashing of rows and columns of the control matrix. To assure the privacy and data security of the study participants, we use a hypertext transfer protocol secure (HTTPS) for data that will be transmitted over the Internet. All experimental procedures need to be previously approved by the local ethics committees. To increase acceptance of the system, these measures need to be communicated to the study participants, their caregivers and family members.

Independent use means that the BCI can be used without the need of an expert or the caregiver to be present, once the initial setup is complete as the end users will always need the help of another person (i.e., a caregiver or family member) to setup the BCI hardware and software. To promote the autonomy of the user, the navigation should be easy and enable the user to independently switch from one application to the next.

Last but not least, users asked for the possibility to personalise the system and adjust it to their specific needs. For instance, they suggested using shortcuts to frequently used applications and actions or the option to select pre-recorded sentences.

3.3.3 User centered evaluation

Our UCD based system stems from the engagement with target end users at all stages of the development and design of the system. The effectiveness of the system is identified by recording how accurate the system was at responded the user. The effort and workload required to operate the system is defined as efficiency and this was identified within an electronic version of the NASA-TLX. This test delivers a task load index which can be used for comparing the effort necessary to operate each tested system. Satisfaction with the system was measured by a Visual Analogue Scale (VAS). This quick method has brought insight into general satisfaction with the system during continuous use. It informs us about the likelihood that the system will be used regularly. Additionally, a customized usability questionnaire was developed to identify user preferences with the system and an extended version of the Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST 2.0 [121]) adapted for BCI research was administered. The rendered version (extended Quest 2.0 [112]) asks users to rate their satisfaction with different aspects of the BCI system, such as dimensions and weight of the system, comfort, ease of use and effectiveness. This test evaluates 12 categories (namely dimension, weight, adjustability, safety, ease of use, well-comfort, effectiveness, service features, reliability/robustness, speed, learnability, aesthetic of design) on

FIGURE 3.3: Overview of electrode systems.

a scale from one ("not satisfied") to five ("very satisfied"). Participants were asked to complete the VAS after each interaction with the BCI and all other questionnaires were completed at the end of the evaluation cycle.

New and better integrated practical electrodes

Several commercially available electrodes and amplifiers were tested to identify the most user friendly and reliable solutions for the final system. This testing assessed key issues like preparation time, signal quality, comfort, and robustness to noise but also technical aspects like signal to noise ratios, delay times, amplifier quality, frequency response.

After initial tests some insufficient electrode systems were excluded and the remaining systems (see Figure 3.3) underwent further advanced tests. The advanced testing phase included different tasks and environments in laboratory settings as well as testing with target end users. The main goal of this testing was to identify which practical electrode systems function best in different tasks and settings to find avenues for development and improvement. Figure 3.3 shows the final systems, namely two dry, one wet and one gel-based system, which were included in the advanced testing phase.

First, the preparation stage included the mounting of each EEG cap and the instruction of the participants. Second, the experimental protocol containing five parts followed:

1. Training. The word "BRAIN" was used to train the classifier. The speller matrix consisted of six rows and six columns and every target letter was highlighted 30 times.

2. First copy spelling run. The participants had to spell the words "SONNE" and "BLUME". Each single word was told to them shortly before they started spelling. If the users had selected a wrong letter they were advised not to correct it. The matrix for training and copy-spelling was the same.

3. Multimedia player run. In this task the subject had to start a slideshow and to look at certain pictures within the XBMC multimedia player. Every command

was announced by the supervisor. Wrong selections were corrected by announcing a correct alternative or the way back to the last correct selection. If the goal could not be reached within 15 selections the task was aborted.

4. Internet browser run. The goal of this task was to navigate to the Wikipedia article about BCI and at the whole article. Every command was announced by the supervisor. Ideally the task could be finished within ten to twelve correct selections. Wrong selections were corrected in the same manner as during the media player task. If the goal could not be reached within 18 selections the task was aborted. The matrix for this task had six rows and a variable number of columns depending on the amount of links on the actual webpage, with a maximum number of 7 columns.

5. Second copy spelling run. This task was performed in the same way as the first copy spelling task. The only difference was that two other words, namely "TRAUM" and "KRAFT", were spelled.

We tested the systems with seven preliminary test subjects and the performed tests provided useful feedback about features of interest, weaknesses, and problems of the different systems. The evaluation of the VAS test reveals a high satisfaction of the users with all systems. Some users scaled systems with lower than 0.5 which means "not satisfied". The three most important features, evaluated by the eQUEST2.0 questionnaire, are (1) speed, (2) effectiveness, and (3) durability together with learnability. The values for the most important feature, speed, were between 3.3 and 3.7. These values were lower compared to the values of the other eleven questions, so the participants were mainly unsatisfied with the speed. During the following advanced testing period the focus was on increasing the speed of the system. Regarding the electrode system, increasing the speed means reducing the time needed for the setup of the system and improve the signal quality.

Friendlier and more flexible BCI software

The provided services have been tested separately before integrating them into the overall system. During the development phase, we followed an evolutionary approach for the definition, implementation and integration of the services. The corresponding feedback was passed on to the software development and was carefully acknowledged for the implementation of the final system.

The evaluation of the provided services already integrated in the overall system was undertaken by a control group of preliminary test users and subsequently brought to target end users. Fourteen test users participated in the study as a control group (9 females, M=28.1 years $\pm$ 8.6, range: 21-46) [110]. Five of the fourteen participants (4 females, M= 36.6 years, $\pm$ 9.3, range 27-46) completed the test protocol on three different occasions, the others performed the test protocol only once. A total of nine end users were recruited for the evaluation of the overall system. Four end users with muscle impairments (f, 80 years; f, 58 years; m, 42 years; m, 51 years) tested the BCI on one occasion each. Additionally, five end users (1 female, M= 37 years, $\pm$ 8.7) who are living with acquired brain injury (Post ABI M= 9.8 years, $\pm$ 3.7) completed the protocol on three different occasions. They tested the spelling application, used the Web browser to post a Twitter message, performed the first level of the find-a-category and the memory cards task and controlled a webcam. They switched between the different applications by selecting the corresponding symbols from the control matrices. The minimum number of selections that were necessary to complete the tasks ranged from 3 selections (webcam) to 18 selections (Web browser/twitter).

1. *Results with preliminary Test Users* The accuracies achieved by the fourteen preliminary test users during the initial BCI session for the individual tasks are depicted in Figure 3.4 [69]. Across all tasks average accuracies were >85% for the five test users that performed 3 sessions, an average of 83% was achieved across the four applications. The accuracy scores across the three sessions remained relatively stable with the average variance <10%. The eQuest2.0 questionnaire revealed that users were quite satisfied with the system and the overall satisfaction score as rated with the VAS was also high (7.48). Through eQuest2.0 they indicated, however, that effectiveness, ease of use and learnability were of the highest importance to them. A major issue was the reliability of the software that had to be restarted at times and a minor concern was the design of the control matrices that contained some "pixelated" symbols.

2. *Results with Target End Users* Seven of the nine target end users involved in the evaluation were able to gain control over the BCI and achieved satisfactory accuracies. Among the end users with muscle impairments, one achieved scores in advance of >90% accuracy for the spelling, games and twitter tasks. Another achieved lower accuracies scores averaging 75% although overall she was pleased with the systems performance on the eQUEST2.0. Two of the initial four end users undertaking the evaluation on one occasion each were unable to operate the BCI. One end user had difficulty focusing on the relatively small symbols in the control matrices and the second had significant muscle spasticity that caused artifacts in the signal. The extended evaluation with end users with acquired brain injury recorded an average accuracy score of 76% across the four applications. The highest overall accuracy was achieved with the Speller (82.07% $\pm$ 13.34) and the lowest with the camera task (64% $\pm$ 22.8).

   Overall, the end users indicated that they were more or less to quite satisfied on the eQuest2.0. Additionally, satisfaction with the BCI on the VAS was reported as high (7.64). The key recommendations from end users included the system being easier to use, reducing fatigue, enabling independent use once the cap was placed and more effective selections. However, users also stated that stability of the software should be improved and that the time needed for one selection was still slow. The items that were rated as most important on the eQuest2.0 were speed, ease of use, effectiveness, reliability and comfort.

3. *Evaluation with Caregivers and Family Members* The final system is meant to be used in a home environment without direct supervision by the BCI researchers. Therefore, the BCI system must be incorporated into the daily routine of the caregivers and family members. The setup of the system should therefore be quick and the main software interface should be easy to configure and not require particular technical skills. Once configured, the system should ideally be a "one-click interface". Hence, in the phase towards the evaluation during independent home use, the focus was more than before on the caregivers and family members, who need to be able to setup the BCI system on their own.

   The findings of the evaluation outlined that seven key areas were important to enhance the user interface: simplification of the interface for the user, the terms and language used, the design, ability to navigate the interface, feedback from the interface, signal acquisition, and the ability to personalise the caregiver interface. Very clear and simple steps through the interface to help in the setup of the BCI were recommended. Recommendations such as a start-up checklist, troubleshooting support when an issue emerges and video instructions were outlined. The terms and language used was also important. Non-technical terms must be used plus the ability to get an explanation by hovering the mouse over the term or click on the icon to find out more. Navigating the interface and the overall design were still not intuitive. Questions were also raised about the feedback the user would get from the system such as what happens when one electrode does not have satisfactory signal. And whether there is enough information for the user to be able to rectify a problem that occurs. Additionally, during testing signal acquisition and quality emerged as one of the most challenging issues particularly for non-expert users. Signal acquisition is fundamental to BCI control and needs to be achieved in the most simplified form with additional information when the user is finding it more difficult.

4. *Evaluation with Therapists* Following on from the initial gathering of user requirements of therapists, we have developed research collaboration with Neurological Occupational Therapists and Speech and Language therapists. The therapists met with the researchers on four occasions (N=10; N=9; N=3; N=3) to help in the definition and development of the cognitive rehabilitation tasks. The technical developers integrated the outcome from the meetings into the application in an iterative process to be reviewed by therapists at the next session. The therapists provided invaluable input into the cognitive rehabilitation in terms of the usefulness of the task, difficulty levels, presentation, language, outcomes, sequencing, number of steps, and application to practice. A framework for the development of cognitive skills has been created against which cognitive tasks were mapped during the collaborative stage of development. The domains emerging within the framework reflect various levels of cognitive complexity [127]: perception, attention and concentration, memory, and executive functions. A total of 53 therapists took part in an overall evaluation of the services offered by the Therapist Station. Following a presentation of BackHome functionalities each participant was asked to evaluate the platform in terms of its application to everyday community based practice on a specifically developed usability questionnaire. Therapists reported that the station would facilitate their day-to-day practice and benefit their client. Recommendations included having a greater range of cognitive rehabilitation tasks, increase the clarity of the results and instructions to support therapists without IT skills.

   Subsequently, 36 of the therapists completed a protocol on the station which included setting up a client as a user, scheduling quality of life assessments and cognitive rehabilitation sessions, and reviewing the results of clients' scheduled assessment and their cognitive rehabilitation session. Each therapist then completed a second questionnaire to evaluate the technical components of using the Therapist Station. Therapists evaluated positively the Therapist Station, they found it easy-to-use and appreciated both functionality and graphical aspect.

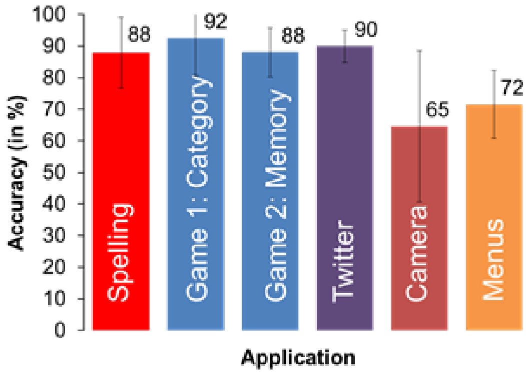

FIGURE 3.4: Average accuracies for the first session achieved by preliminary test users for the five tasks and for switching between tasks.

Better Telemonitoring and Home Support

Also in the conception and development of the TMHSS a UCD methodology has been adopted. Similarly to [128], questionnaires and focus groups in relation to general requirements of the sensor-based TMHSS were run during the system design early stages. Participants were asked about its general requirements. For example: "How would you like to get monitored your physical and psychological status?"; or "What would you like to have at home to feel more secure, video cameras detecting intruders, sensors identifying anomalies?". The same participants met four times in two hours sessions to discuss aspects related to the different technical issues and to assure consistent results. The main objective was to extract information from users related to the interaction modes and also about sensors and devices preferences in relation to the general requirements of the system. A moderator carried out the sessions and an observer took field notes.

General results from the questionnaire showed that users considered telemonitoring and home support as an opportunity to facilitate their daily life, they felt quite confident with the use of technology and they preferred easy to use devices and adapted interfaces. Participants reported that data collected by the sensor-based system should be provided in a secure and simple way, being worried about their privacy and the use of their personal information.

According to the evolutionary prototyping, a first version of the implemented sensor-based system was installed, tested and evaluated in a test user's home in Barcelona. The corresponding user is a 40-year-old woman who lives alone[11] [10]. On the one hand, collected data was used to recognize habits as well as to a preliminary study aimed at assessing quality of life. On the other hand, feedback from the user was used to improve the system in terms of performance and usability.

Recommendations

The outcome from the user centred evaluation of the system as well as the requirements gathered at the earlier stages of the development life cycle gives as output a list of recommendations that have been carefully addressed during the system development. The summary of those recommendations, ordered according to the priority list, together with the corresponding user requirements, is shown in Figure 3.2.

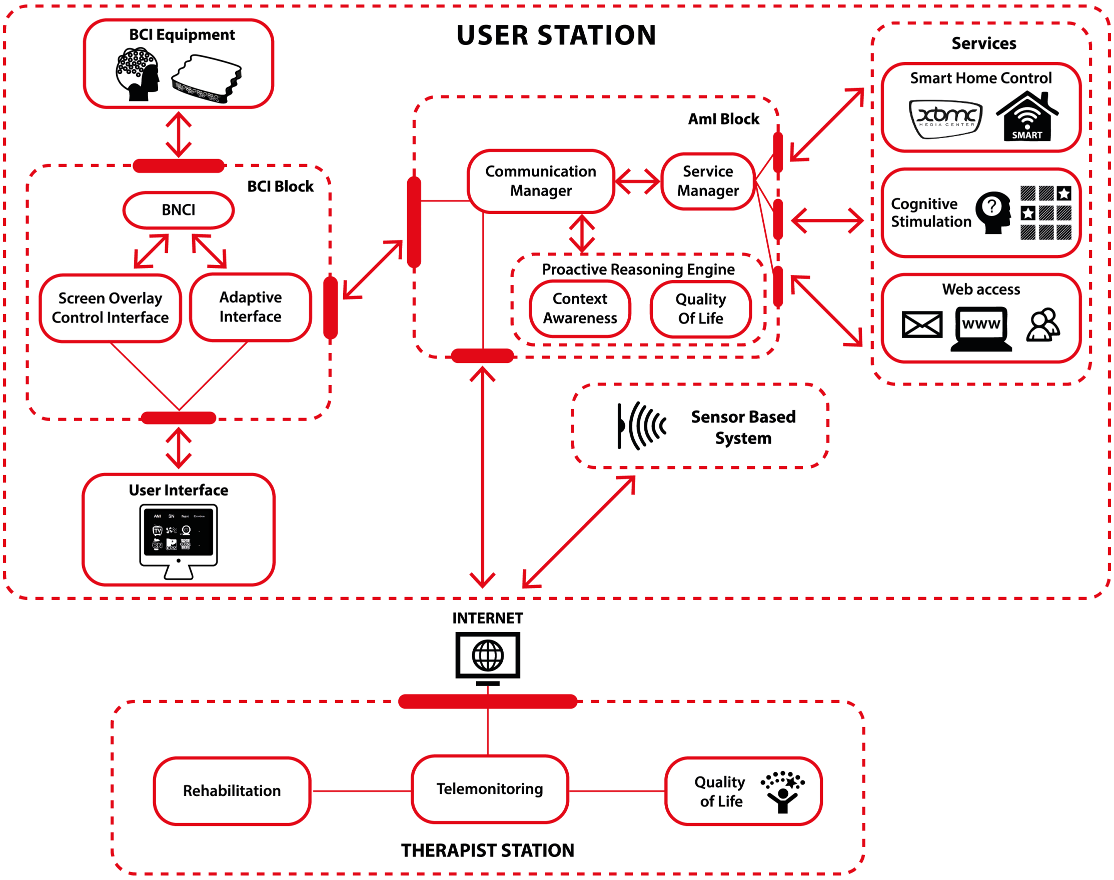

FIGURE 3.5: BackHome architecture overview.

3.4 The final Backhome system: architecture and components

The BackHome system integrates the developments undertaken through the UCD life cycle, the innovation driver towards the goal of advancing a practical solution for independent home use. It includes a User Station with wireless EEG biosignal acquisition system, a dynamic environmental sensor network, and an easy-to-use BCI software to access a range of services to facilitate activities of daily living. Additionally, the Therapist Station provides services for remote planning and assessment of user activity, rehabilitation tasks and quality of life indicators.

3.4.1 System arquitecture

Figure 3.5 shows the high level modular and distributed architecture of the BackHome system (which we labeled as key innovation i)), accessed through two interconnected stations: i) User Station and ii) Therapist Station.

The end user interacts with the User Station, the BCI-based subsystem which comprises the modules responsible for the BCI components (a screen user interface together with a BCI block and BCI equipment) connected to the services of Smart Home control, cognitive stimulation and Web access through the Ambient Intelligenge (AmI) block, which holds the intelligence of the system. To execute and control its functionalities the User Station (including the BCI equipment and home sensors and actuators) must be installed and completely integrated at the user's home. The AmI block is the central control and intelligence component of the User Station. It communicates and interacts with all other components of the system. It provides control to all services for Smart Home control, cognitive stimulation and Web access, receives the user selections from the BCI system and reports indicators relevant for the user assessment to be checked out through the Therapist Station. The BCI block is connected to the user through the BCI hardware and the User Interface, which displays the stimuli for the BCI and the interfaces of all the services. With the proposed BCI, all applications can be operated via control matrices that were first proposed in [129] for a spelling system. As control signals the BCI uses event-related potentials (ERPs) that can be extracted from the EEG. Of these ERPs the P300 is often the most prominent [130]. During stimulation, rows and columns of the matrix are highlighted in random order. To operate the system, users are asked to attend to the symbol (e.g., a letter or a command) in the matrix that they want to select and silently count whenever it is highlighted. The rows and columns including the target symbol elicit the ERP response. Thus, the system can identify the target symbol as the symbol at the intersection of the row and column that elicited the P300 response and execute the desired action. The BCI components together allow the user to control the User Station with services and actuators and receive feedback from sensors and services.

The Therapist station is a Web-based easy-to-use service which allows a remote therapist, a teleassistance service operator, or another professional, to access information stored in the cloud and gathered from users and sensors around them: users' inputs, activities, selections and sensor data. This information takes the form of system usage reports, rehabilitation tasks results and quality of life assessment, and supports those professionals to make informed decisions on rehabilitation planning and personalisation as well as remote assistance and support action triggering. The scalable and robust cloud storage of data and ubiquitous Web access provides the needed flexibility in order to get the maximum potential out of the telemonitoring and home support features because the therapist can access the station at any moment with any device that is connected to the Internet.

3.4.2 The User Station

As shown in 3.5, the system offers a set of flexible and extensible services: Smart Home control, cognitive stimulation, and Web access. Smart Home control service is aimed at giving control over the environment, as well as over useful devices. Thanks to that service, the user is able to control home devices (e.g., a light, a fan, a radio) as well as to interact with the XBMC multimedia player. Cognitive stimulation services allow users to improve their cognitive capabilities by performing cognitive rehabilitation tasks assigned by a therapist or by using their creative skills through Brain Painting. Web access services enable participation and inclusion by offering users the possibility to engage in social interaction through the Web, such as Web browsing, emailing and twittering.

Practical electrodes

Based upon the user feedback and the results of an advanced electrode testing described in section 3.3.3, a new biosignal acquisition system called g.Nautilus was developed [107] by partner company g.tec medical engineering[1] and is shown in Figure

[1]http://www.gtec.at/Products/Hardware-and-Accessories/g.Nautilus-Specs-Features

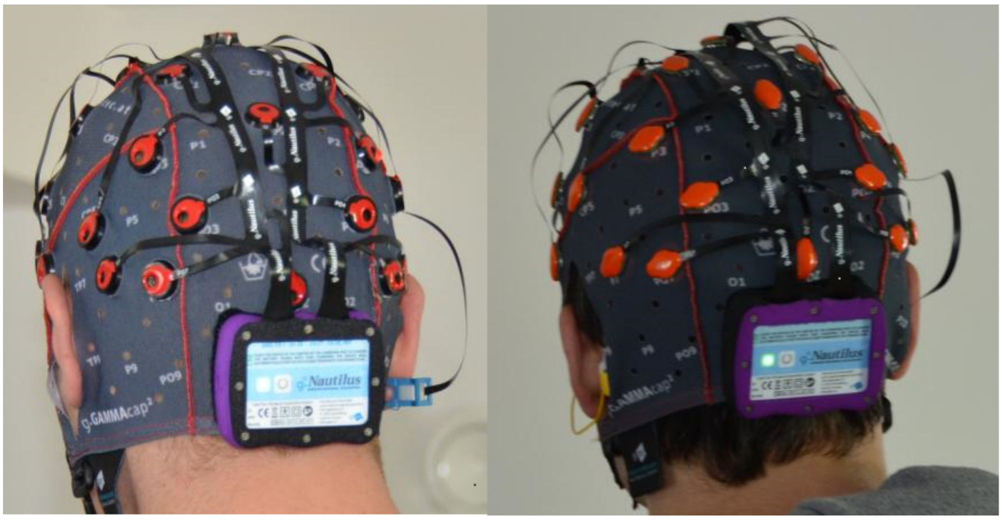

FIGURE 3.6: g.Nautilus headset (by company g.tec medical engineering) with gel based (left) and dry (right) electrodes.

3.6. Its biosignal amplifier uses wireless technology to transmit the EEG signals with 24 bit resolution. The signal of each EEG channel is highly oversampled in order to keep the signal to noise ratio (SNR) high at the offered rates of 250 Hz and 500 Hz. Furthermore it is capable of measuring the electrode-skin impedance at each electrode position for both gel based and dry electrodes.

A base station which is connected to the host system through USB is used to receive the recorded and digitized EEG signals. The biosignal amplification unit consists of the headset including the wireless biosignal amplifier electrodes, an EEG cap and the base station including a USB cable for connecting it to the host computer and a QI compatible wireless charging station. The 34 electrodes including reference channel and ground are pre-connected to the amplifier using a preconfigured set of electrode positions.

The user interface of the headset consists of the power switch and the status LED. Both are located on the top face of the head set. The electrodes are connected to two groups of monopolar amplifiers. The first group is connected to the ground electrode and the first 16 EEG channels and the second group is connected to the electrode positions 17-to 32 and the reference channel. The main advantage of this system which we labeled as key innovation ii) is its wireless technology and the choice of dry electrodes. Both factors have often been criticized from test users as well as target end users when they used other non-wireless technologies. Most notably the fact that no hair wash is needed when using dry electrodes is a big increase in terms of usability. Furthermore the quick and easy montage of the system makes it also practical and comfortable especially for target end users.

Easy to use software: The implemented Services

This long section describes all the novelties related to the user friendly software to access multi-functional applications through BCI which we labeled as key innovation iii). The BCI user interface is based upon the Screen Overlay Control Interface (SOCI)

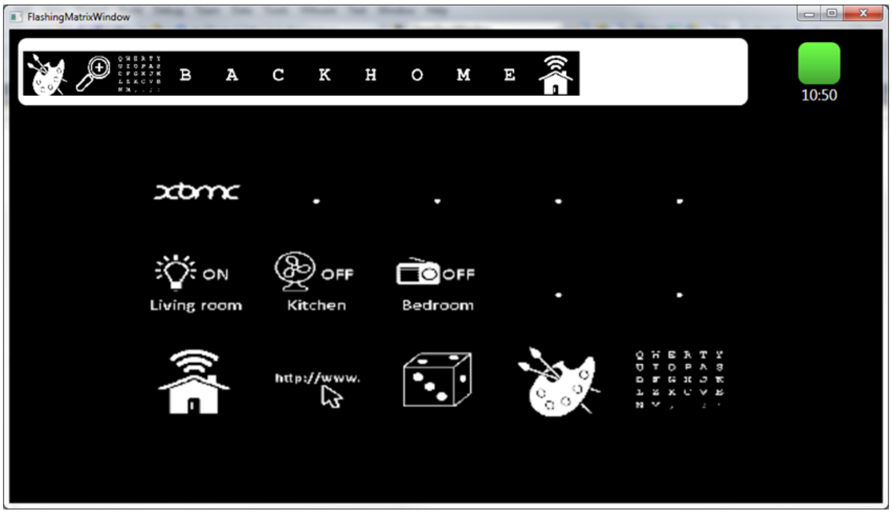

FIGURE 3.7: Primary User Interface showing the main screen of the Smart Home service.

library [131], which allows embedding the BCI stimuli on top of the native interface of any user application and communicates with the BCI hardware via a network connection. Along with the integration of SOCI the Primary User Interface (PUI) has been redesigned according to the recommendations expressed by the users during the UCD tests summarized in Section 3.3.3. Now, for instance, the number of lines, columns, the spaces in between and thus the display size of the individual icons are now defined depending upon users' capabilities. Masks which are smaller are automatically centered by SOCI within the visible area. Alternatively the new version of the Application ConTrol and Online Reconfiguration (ACTOR) protocol, described in [132], allows the application to explicitly position its masks on the screen.

Figure 3.7 shows the PUI, which is split into three sections. On top of the screen a history bar shows the last selections made. On the top right side thereof the current time of the day is displayed along with the quality of the EEG signal recorded. The middle section displays the active P300 matrix for the currently selected service or service group, for example the Smart Home group for interaction with user's environment and the multimedia player. The bottom row of the screen displays the menu which allows to switch between the different services and service groups (i.e., Smart Home control, Web access, Cognitive Rehabilitation Games, Brain Painting, and Speller). When the user selects one of the icons on the screen the system automatically activates the selected service, service group and displays the corresponding masks. The masks available for each service and service group are described in detail along with each service provided by the BackHome system in the following subsections.

An easy to operate user interface was developed for the non-expert caregiver , shown in Figure 3.8, that enables him to start the system with just one-click, to create the classifier (in training mode) and to shutdown (Quit) the BCI system. Furthermore, when the system is started it automatically activates the check signals mode and starts the signal acquisition. This simplifies the mounting of the electrode cap as the signal quality display is visible during the whole procedure. The interface has been designed to optimally guide the care giver through the setup process step by step and provide

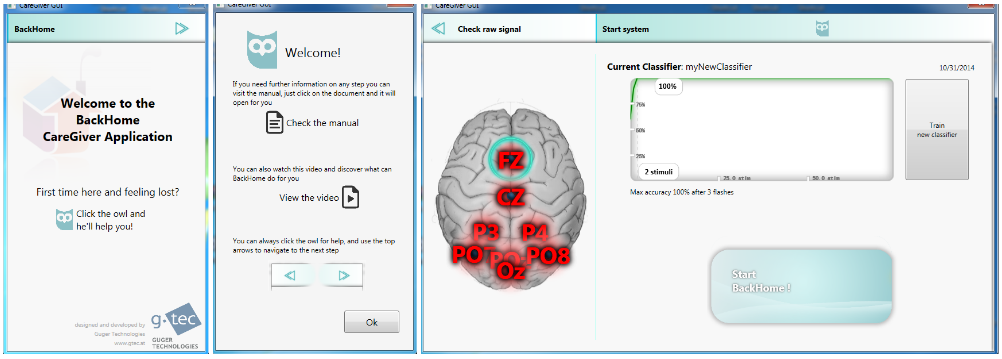

FIGURE 3.8: The caregiver interface. Three screenshots of the welcome window (on the left), the help window with links to the manual and a video (in the middle), and the signal quality window with a plot of the trained classifier (on the right)

access to help and support information on every screen. Only those information and controls are shown which are necessary to accomplish the current step or advance to the next one when finished or go back to the previous one.

The system offers a set of innovative, flexible and extensive services ([110]) for Smart Home control, cognitive stimulation, and Web access. All those services rely on a P300 spelling and control system in which the highlighting of options happens with freely selectable images (famous faces) instead of just changing the colour of the background [133]. Users interact with the system through two separated screens: one for the BCI matrix and one for the selected service.

The dynamic stopping method is an algorithm integrated into the software specifically with home use in mind whose purpose is to increase the selection speed by determining the optimal number of sequences during usage and dynamically making a selection (stopping) when a probability threshold is reached. Furthermore, it minimizes the number of false selections by suppressing unintended selections (if the user is not looking at the screen, for instance).

Those are the types of services currently offered by the BackHome system:

1. *Smart Home Control.* Smart Home control service is aimed at giving control over the environment, as well as over useful devices (e.g., a light, a fan, a radio) as well as to interact with the XBMC multimedia player.

   Smart home devices, which provide control over the software environment and free standing electrical goods, are installed in the user's home so that the user is able to control them through the BCI. The current system integrates ON/OFF switches and power meters connected with appliances (e.g., lights, radio players, etc.). In particular, we use Everspring AN158, a switch plug-in between standard wall outlets and appliances. It can switch ON/OFF as well as measure the electrical consumption. The end user controls the appliances via a P300 control interface (in the primary User Interface in Figure 3.7, three appliances are shown: a light, a fan, and a radio, together with the information regarding their location in the house).

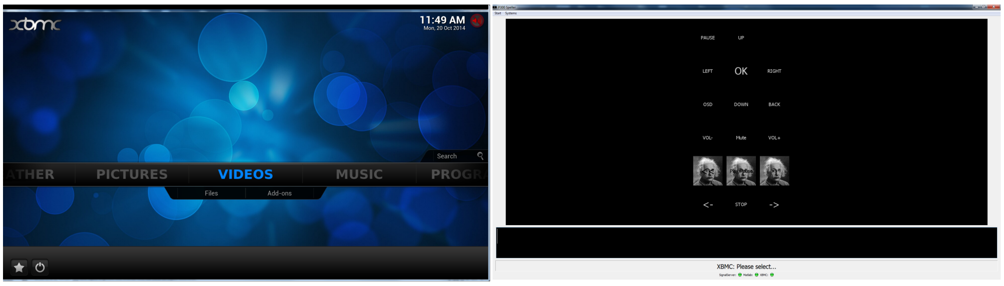

FIGURE 3.9: The Primary User Interface to control the XMBC multimedia player.

Apart from controlling devices through the P300 control interface, the user can also interact with a multimedia player to see photos, videos, movies, and so on. The implemented media player application is XBMC[2], see Figure 3.9. XBMC is a free and open source media player application and is designed to be controlled with a remote control or game controller. With these control devices the amount of input dimensions are very limited compared to mouse control or keyboard control, which is the main reason why we decided to use XBMC. Another feature which makes XBMC ideal to be controlled with our BCI system is the predefined network interface. We use a raw TCP socket based interface with a JavaScript Object Notation - Remote Procedure Call (JSON-RPC) protocol. A big advantage of this network based control is that XBMC can run on a different PC than the P300 system. This is due to the fact that the XBMC was designed for a game-console.

2. *Cognitive Stimulation.* Cognitive stimulation services allow users to improve their cognitive capabilities by performing cognitive rehabilitation tasks assigned by a therapist i.e., Activities of Daily Living, Find a Category, and Memory ([127]), or by using their creative skills through Brain Painting ([134]).

   Cognitive Rehabilitation. Together with Occupational Therapists and Speech Language Therapists, three cognitive rehabilitation tasks have been defined, developed and integrated defined to improve cognitive capabilities of users. Each game consists of a P300 matrix and an interface in which the game is shown (see Figure 3.10). Each task belongs to one level of complexity in the cognitive-skills pyramid (starting from Perception, then Attention and Concentration, then Memory, and then Executive functioning, the most complex cognitive skill) and has three levels of difficulty that the therapist may select through the therapist station to personalize the therapy plan for each end user. Results are shown to the user after each play and are also sent back and presented to the therapist who may control user's evolution and fine tune the personalization of the cognitive therapy. The implemented tasks are: Memory-cards, aimed at enhancing memory skills [127]; Find a Category, which provides users with activities for improving semantic and reasoning skills essential in cognitive rehabilitation, language and learning; and Daily-life activities, which prompts users to decide the order of tasks of a daily life activity (e.g. frying an egg) and therefore allows users to develop executive functioning skills that can be applied to real life tasks.

[2] Available: http://xbmc.org/. [Accessed 20. 10. 2014]

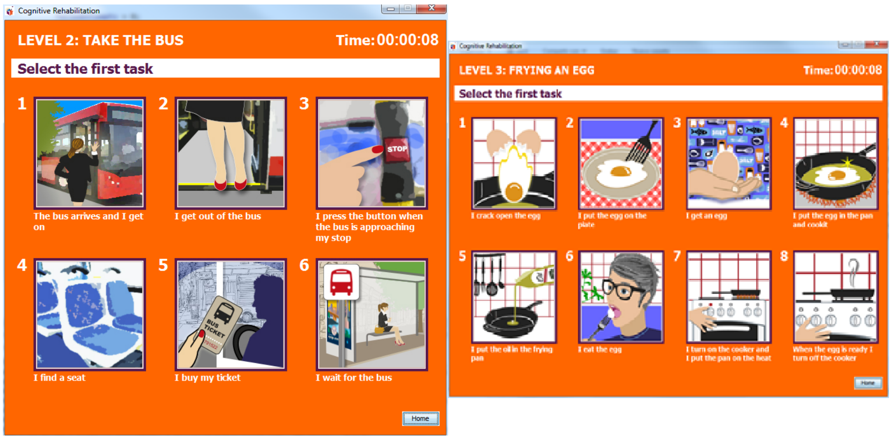

FIGURE 3.10: Screenshot of Daily-life activities game (levels 2 and 3).

Brain Painting. The Brain Painting application allows users to create paintings on a virtual canvas. Selections are made via a 6 x 8 black and white, P300 based control matrix. It allows users to choose a grid size, move the cursor, choose object form, size and color and level of transparency and zoom in and out of the picture. Once the user chooses a specific color, the selected object appears on the screen. Erroneous selections can be corrected by selecting the undo button. The application was evaluated with preliminary test users [134] and target end users [45]. BackHome's Brain Painting service has been permanently installed at two target end users' homes at Würzburg. Results of this long term evaluation that is ongoing were reported in [49], [135], [136]. Both participants were diagnosed with amyotrophic lateral sclerosis (ALS) and have an artistic background. The first user (A) is a 74 year old female and the second (B), a 73 year old male. After an initial phase in which users as well as caregivers and family members were trained to set up the system, they used it independently. In case of technical errors, they were solved via remote control. After every session users were prompted to indicate their perceived level of control, satisfaction and frustration. User A painted for 403 hours in 271 sessions and user B painted for 65 hours in 58 sessions. Their overall satisfaction with the system during these sessions was high and in the majority of sessions, the level of control was rated as either medium or high by both users [136]. Since the installation in January 2012 user A has created numerous paintings that she presented at exhibitions in Easdale, Scotland and Würzburg, Germany. One of her paintings was featured on the cover of the scientific journal Brain. However, the impact the system has for these users is best expressed in a statement from her: "Brain Painting makes me happy and satisfied every time again, if it works - if not, then frustration and disappointment. Fortunately this happens in only few cases. Brain Painting completely changed my life. I can paint again and be creative again using colours [. . .]" (Nov 2013). Figure 3.11 shows a brain painting created by user A.

3. *Web Access.* One of the main objectives of BackHome is to support people with limited mobility access the Internet and all the online services it has to offer to enhance social inclusion. Thus, services that allow users to access World Wide Web have been provided. In particular, a new Web browser and an email reader have been implemented and integrated. Figure 3.12 shows the primary User Interface for Web access services: Web browser, Twitter, eMail, as well as two personalized

FIGURE 3.11: Brain Painting entitled "Die EU Muskeltiere - the EU Muscleteers", with kind permission from the artist.

FIGURE 3.12: PUI of the Web access services.

shortcuts, one linked to a weather forecasting service geo-localized depending on the installation and one linked to the preferred online newspaper.

Web Browser. The Web browser was developed for the BackHome system using the Qt software framework. It enables bidirectional communication between the browser and the BCI system. Each hyperlink displayed on the webpage is assigned a letter (or a combination of letters for more than 26 links on a page) and depicted next to it. These hints are also displayed in the P300 control matrix. Thus, each control matrix contains only as many elements as links on the web page, plus an additional 15 control elements that were needed to navigate the webpage (e.g. scroll up/down), pause the flashing to look at a page and other purposes. Pausing the flashing is automated in the final version of the prototype by detecting whether the attention is directed at the matrix or the application. The control matrices can contain up to 84 (14 x 6) elements. Hence, a maximum of 69 hyperlinks can be selected per page. If a text entry field is selected, the letter and numeral matrix is automatically displayed. Compared to a similar P300 Web browser proposed in [137], the selection time can be reduced by about 25% with the current implementation.

The Web browser was evaluated both as a standalone version, together with the multimedia player and the P300 speller [138], and integrated into the current system. In the study by [138] preliminary test participants and target end users were asked to search for the word "BCI" with the Web browser and navigate to the corresponding Wikipedia article. A minimum of 12 selections were needed to

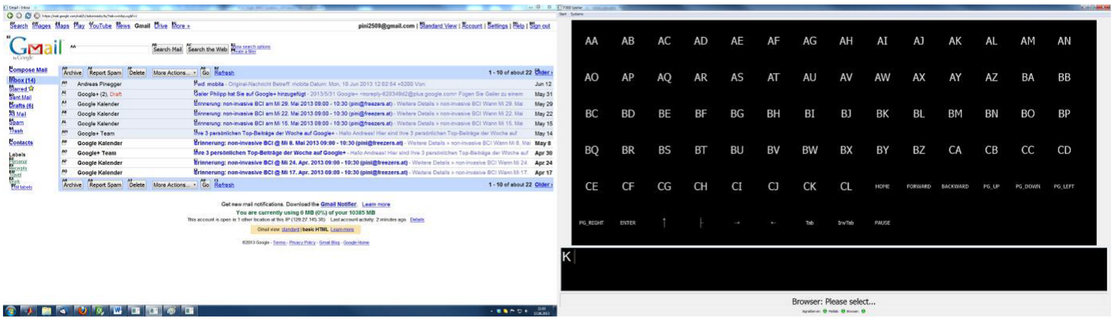

FIGURE 3.13: Screenshot of the Gmail home page(left) and the P300 controller(right).

complete the task. In the study by [110], participants posted a short twitter message (a minimum 18 selections were needed). Preliminary test controls could operate the Web browser with high accuracies (88% in [138] and 90% in [110]) and the majority of end users could also control it (with lower accuracies) and felt in control while using it.

Email. Email control was realized using the Web browser described above. The challenge of this system is that webmail pages are very complex constructed and many of them use content dynamically created at the client-side. So far the link detector of the implemented Web browser does not support such complex webpages. However, the system was successfully tested with the HTML version of Gmail [3], see Figure 3.13. It was demonstrated that users can easily read and write emails with this system [139]. The same solution was used to implement Twitter, Weather and News controls with good results.

3.4.3 Telemonitoring and Home Support System

The BackHome system includes a sensor-based telemonitoring and home support system (TMHSS) that is able to recognize habits of the end-user, automatically assess quality of life, and capture statistics about the BCI usage. In fact, this TMHSS is able to observe the evolution of the daily life activity of the end user using a BCI [101] , which we have labeled as key innovation iv).

The high-level architecture of the Sensor Based TMHSS is depicted in Figure 3.14. As shown, its main components are: home; middleware; intelligent monitoring system; and therapist station. Let us summarize here the main features of the implemented system, which is presented with more details in [10], [140] and [141].

Home

At home, the TMHSS is composed of a network of wireless environmental sensors connected to a collector for indoor monitoring. As for indoor activities, we use presence sensors (i.e., Everspring SP103), to identify the room where the user is located (one sensor for each monitored room) as well as temperature, luminosity, humidity of the corresponding room; a door sensor (i.e., Vision ZD 2012), to detect when the user enters or exits the premises; electrical power meters and switches, to control leisure activities

[3] http://mail.google.com

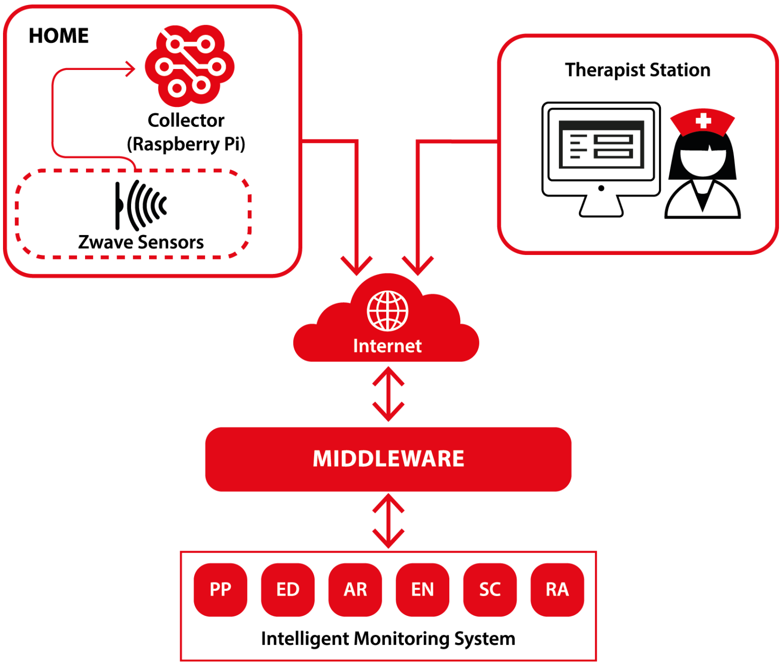

FIGURE 3.14: Main components of the sensor-based system focused on the intelligent monitoring.

(e.g., television and pc); pressure sensors (i.e., bed and seat sensors), to measure the time spent in bed and on wheelchair. The system is also composed of a network of environmental sensors that measures and monitors environmental variables like temperature, but also potentially dangerous events like gas leak, fire, CO escape and presence of intruders. From a technological point of view, all the wireless sensors are z-wave[4]. They send the retrieved data to a collector (based on Raspberry pi[5]) located at user's home. The solution relies on z-wave technology for its efficiency, portability, interoperability, and commercial availability. In fact, as opposed to other wireless solutions (e.g., ZigBee), z-wave sensors are able to communicate with any z-wave device. Moreover, we adopted a solution based on Raspberry pi because it is easy-to-use, cheap, and scalable.

The collector unit collects all the retrieved data and securely redirects them to the cloud middleware where they are processed, mined, and analyzed. Besides real sensors, the system also comprises "virtual devices", software elements that mash together information from two or more sensors in order to make some inference and provide new information. As a consequence, the sensor-based system is able to perform more actions and to be more adaptable to the context and the user's habits. Furthermore, the mesh of information coming from different sensors can provide useful information to the therapist. In other words, the aim of a virtual device is to provide useful information to track the activities and habits of the user, to send it back to the therapist through the therapist station, and to adapt the User Station, with particular reference to its user interface, accordingly.

[4]http://www.z-wave.com/
[5]http://www.raspberrypi.org/

As for outdoor activities, we are using the user's smartphone as a sensor by relying on MOVES[6], an app for smartphones able to recognize physical activities (such as walking, running, and cycling) and movements by transportation. MOVES is also able to store information about the location in which the user is, as well as the corresponding performed route(s). MOVES provides an API through which is possible to access all the collected data. Among the activity trackers currently on the market, we selected Moves because it does not need user intervention being always active in the background and because it does not need any extra device.

Information gathered by the sensor-based system is also used to provide context-awareness by relying on ambient intelligence (AmI) algorithms [142]. In particular, thanks to the adopted sensors we provide adaptation, personalization, alarm triggering, and control over the environment through a rule-based approach that relies on a suitable language, ATML, as we have described in [143]. This TMHSS is able to continuously gather data from the room in which the users are spending their time when they are at home, to recognize and study the end-user habits ([144]) and to automatically assess user's quality of life ([145]), as it was preliminary assessed in [104].

Middleware

The telemonitoring system by definition needs to be interoperable, extensible and scalable. In order to deal with such requirements the design of the system architecture was based on a Service Oriented Architecture (SOA) framework [7], specifically the WSO2[8] framework with APIs for third part integration. Thus, each component of the system was built as web service itself and communicate through the REST protocol. This protocol is selected since it works over Hypertext Transfer Protocol (HTTP) and allows relaxed interoperability between different components.

The middleware, which is the set of core components of the architecture, is composed by independent web services that provide not only scalability and interoperability but also securely interconnect the main components of the system, i.e. the home, the intelligent monitoring system, as well as the therapist station. Its main functional components are:

- The Application Programming Interface (API) façade, which encapsulates a set of information services provided by the intelligent monitoring system in order to be consumed by external applications (e.g. the therapist station). Internally, this component securely dispatches all requests of information from outside and redirects them to the enterprise service bus. This service contains policies and protocols to handle load balancing and concurrency.

- The Enterprise Service Bus (ESB), which orchestrates the communication between internal components avoiding ad hoc communication. The ESB makes the system more extensible and flexible to changes by doing all components communicate through it.

[6]http://www.moves-app.com/
[7]www.oasis-open.org/
[8]www.wso2.com/

- The Security Manager (SM), which provides mechanisms to user authentication, and services authorization. This component manages the session IDs to the system as well as the Universally Unique Identifiers (UUIDs) that identify uniquely the users and the services which have access to.

- Notification service (NS), which is a mechanism for sending asynchronously data (e.g., events, emergencies, rule actions) generated from the consumer (e.g., Intelligent Monitoring) to a receiver or client (e.g., therapist station)

Intelligent Monitoring

In order to cope with data necessities of the actors of the system (i.e., therapists, caregivers, relatives, and end-users themselves), an Intelligent Monitoring (IM) system has been designed. It is aimed to continuously analyze and mine the data through 5-dimensions: detection of emergencies, activity recognition, event notifications, summary extraction, and rule triggering. In order to achieve these objectives, the IM system is composed of the following modules (see Figure 3.15): PP, the pre-processing module to encode the data for the analysis; ED, the emergency detection module to notify, for instance, in case of smoke and gas leakage; AR, the activity recognition module to identify the location, position, activity- and sleeping-status of the user; EN, the event notification module to inform when a new event has been detected; SC, the summary computation module to perform summaries from the data; and RA, the risk advisement module to notify risks at runtime.

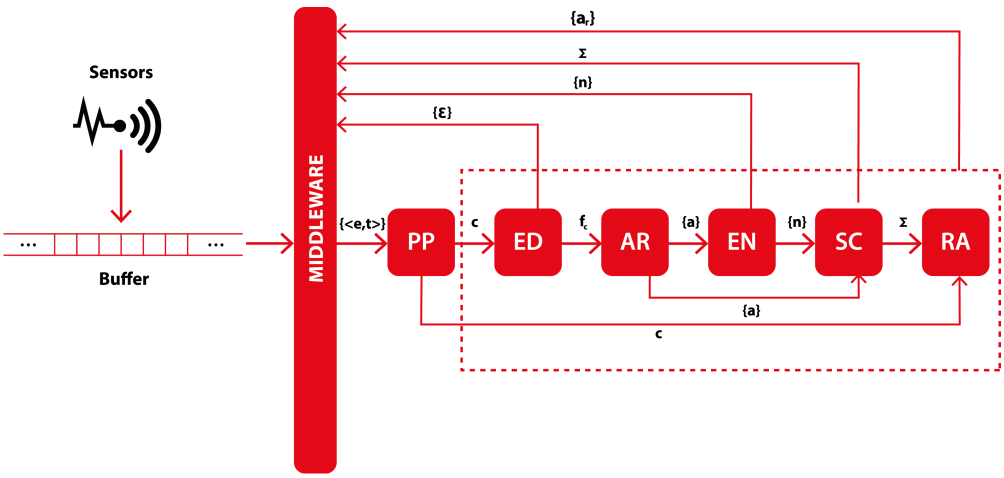

FIGURE 3.15: The flow of data and interactions among the modules in the proposed approach.

1. *Pre-Processing (PP).* IM continuously and concurrently listens for new data. The goal of PP is to pre-process the data iteratively sending a chunk c to ED and also RA according to a sliding window approach. Starting from the overall data streaming, the system sequentially considers a range of time $|t_i$ - $t_{i+1}|$ between a sensor measure s_i at time t_i and the subsequent measure s_{i+1} at time t_{i+1}. Thus, the output of PP is a window c from t_s to t_a, where t_s is the starting time of a given period (e.g., 8:00 a.m.) and t_a is the actual time. Thus, each chunk is composed of a sequence of sensor measures s; where s is a triple $< ID, v, t >$, i.e., the sensor ID, its value and the time in which a change in the sensor status is measured. Figure 3.16 shows an example of a chunk composed by four sensors measures.

195	24.10	2014-02-24 10:21:54	195	24.10	2014-02-24 10:30:04	177	100	2014-02-24 10:31:55	195	24.10	2014-02-24 10:34:54

FIGURE 3.16: Example of a chunk composed of four sensor measures.

2. *Emergency Detection (ED).* ED module aims to detect and inform about emergency situations for the end-users and sensor-based system critical failures. Regarding the critical situations for the end-users, an emergency is risen when specific values appear on c (e.g.; gas sensor ID, smoke sensor ID). Regarding the system failures, ED is able to detect when the end-user's home is disconnected from the middleware as well as a malfunctioning of a sensor (e.g., low battery). The former is implemented by a keepalive mechanism in the Raspberry pi. If no signals are received from the Raspberry pi after a given threshold, an emergency is risen. The latter is implemented by using a multivariate gaussian distributions of sensor measurements on c. If the corresponding total number of measures is greater than a given threshold, an emergency is risen. Each emergency is a pair $< s_i, l_{\epsilon i} >$ composed of the sensor measure s_i and the corresponding label $l_{\epsilon i}$ that indicates the corresponding emergency (e.g., fire, smoke). Once the ED finishes the analysis of c, the list of emergencies ϵ is sent to the middleware, whereas c, filtered from the critical situations, is sent to AR.

3. *Activity Recognition (AR).* In the current implementation, the system is able to recognize if the users are at home or away and if they are alone; the room in which the users are (no-room in case they are away, transition in case they are moving from a room to another); the activity status (i.e., active or inactive); and the sleeping status (i.e., awake or asleep).

   To recognize if the users are at home or away and if they are alone, we implemented a solution based on machine learning techniques [70]. The adopted solution is a hierarchical classifier (see Figure 3.17) composed of two levels: the upper is aimed at recognizing if the users are at home or not, whereas the lower is aimed at recognizing if the users are really alone or if they received some visits. The goal of the classifier at the upper level is to improve performance of the door sensor. In fact, it may happen that the sensor registers a status change (from closed to open) even if the door has not been opened. This implies that AR may register that the user is away and, in the meanwhile, activities are detected at user's home. On the contrary, AR may register that the user is at home and, in the meanwhile, activities are not detected at user's home. Thus, we first revise the data gathered by AR searching for anomalies, i.e.: (1) the user is away and at home some events are detected and (2) the user is at home and no events are detected. Then, we validate those data by relying on Moves, installed and running on the user smartphone, and the supervision of the user. Using those as an "oracle", we build a dataset in which each entry is labeled depending on the fact that the door sensor was right (label "1") or wrong (label "0").

   The goal of the classifier at the lower level is to identify whether the user is alone or not. The input data of this classifier are those that has been filtered by the upper level, being recognized as positives. To build this classifier, we rely on the novelty detection approach [146] used when data has few positive cases (i.e., anomalies) compared with the negatives (i.e., regular cases); in case of skewed data.

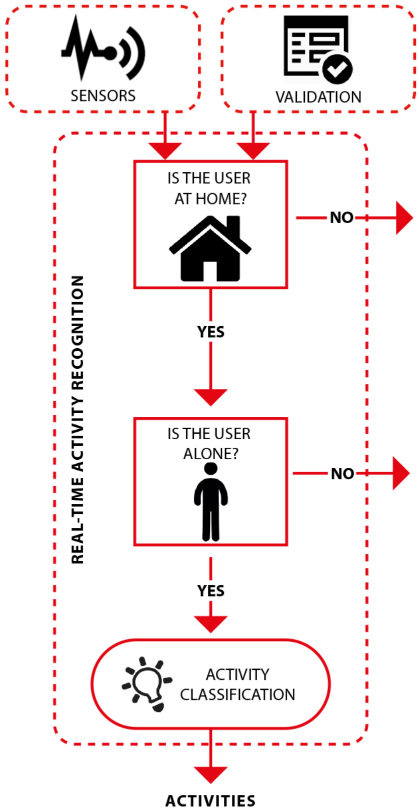

FIGURE 3.17: The hierarchical approach in the activity recognition module.

To measure the activity status, we rely on the home automation sensors. By default, we consider as "active" the status of the users when they are away (the corresponding positions are saved as "no-room"). On the contrary, when the users are at home, AR recognizes them as "inactive" if the sensor measures at time t_i that user is in a given room r and the following sensor measure is given at time t_{i+1} and the user was in the same room, with $t_{i+1} - t_i$ greater than a given threshold θ. Otherwise, the system classified the user as "active".

Finally, sleeping is currently detected by relying on the presence sensor located in the bedroom and the pressure mat located below the mattress. In particular, we consider the presence of the user in that room and no movements detection (i.e., the activity status is "inactive") together with the pressure of the mattress.

Thus, the output of AR is a triple $< t_s, t_e, l >$, where t_s and t_e are the time in which the activity has started and has finished, respectively, and l is a list of four labels that indicates: the localization (i.e., home, away, or visits), the position (i.e., the room, no-room, or transition), the activity status (i.e., active or inactive), and the sleeping status (i.e., awake or asleep). To give an example, let us consider Figure 3.18 where the same chunk of Figure 3.16 has been processed by AR.

2014-02-24 10:21:54	2014-02-24 10:30:04	home, bedroom, inactive, asleep	2014-02-24 10:31:55	2014-02-24 10:34:54	home, bathroom, active, awake

FIGURE 3.18: Example of a chunk after the AR processing.

4. *Event Notification (EN).* By relying on a set of simple rules, EN is able to detect events to be notified. Each event is defined by a pair $< t_i, l >$ corresponding to the time t_i in which the event happens together with a label l that indicates the kind of event. In particular, according to user requirements and therapist's focus groups, we decided to detect the following kind of events: leaving the home, going back to home, receiving a visit, remaining alone after a visit, going to the bathroom, going out of the bathroom, going to sleep, and awaking. These events allow to study activity degradation as well as improvement/worsening of the overall quality of life. Nothing prevents to consider further notification and/or to change them in case requirements change or further needs arise. Following the example, in Figure 3.16, an event is the pair $< 2014-02-2410:31:55, going\,to\,the\,bathroom >$.

5. *Summary Computation (SC).* Once all the activities and events have been classified, measures aimed at representing the summary of the user's monitoring during a given period are performed. In particular, two kinds of summaries are provided: historical and actual. As for the historical summary, we decided to have a list of the activities performed during (i) the morning (i.e., from 8 a.m. to 8 p.m.), (ii) the night (i.e. from 8 p.m. to 8 a.m.), (iii) all the day, (iv) the week (from Monday morning to Sunday night), as well as (v) the month. In particular, we monitor: sleeping time; time spent outdoors; time spent indoors; time spent performing indoor activities; time spent performing outdoor activities; number of times spent in each room; and number of times that the user leaves the house. As for the actual summary, we are interested in monitoring: the room in which the users are; if the users are at home or not; the number of times that they leave the home; sleeping time; activity time; and number of visits per room. As a final remark, let us note that all emergencies, activities, notifications, and summaries are stored in a database to be available to all the involved actors.

6. *Risk Advisement (RA).* RA is aimed at advising therapists about one or more risky situations before they happen. The module executes the corresponding rules at runtime according to the sequence of sensor measures coming from the PP as well as the summary provided by the SC. Figure 3.19 sketches how RA works and which are its main components and interactions. Through the healthcare center, therapists access to an ad-hoc user interface to define the rules corresponding to risks. Those rules are automatically coded in a suitable language, namely ATML [143], and then translated in Drools[9] format by the Rule Builder and stored in the Knowledge-Base of Rules (KBR). RA continuously processes data coming from the other modules of the IM and acts according the defined rules in KBR. In particular, it analyzes the entire chunk c from PP, the list of activities a from AR, and the complete summary Σ from SC. The actions $\{a_r\}$ triggered by RA are sent to the middleware that is in charge of actuate in consequence sending the corresponding advisement to the healthcare center.

   To implement the RA we relied on Drools, a rules management system that provides a rule execution server, and a web authoring and rules management application. A rule is a quadruple $< i, v, o, a_r >$, where i is the item that has to be verified (e.g., a room, the number of slept hours) according to a given value v (e.g., bedroom, 4 slept hours); o is the logic operator (i.e., and, or, not) and a "null" operator in case there is only one term; and a is the action to be performed (i.e., send a notification, an alarm, or an email).

[9] http://www.drools.org/

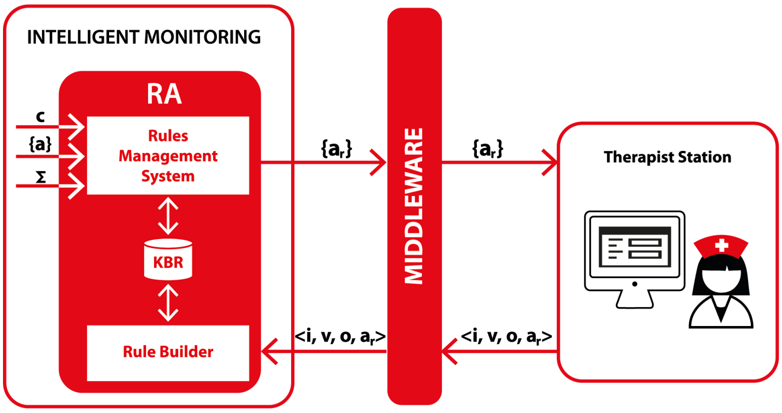

FIGURE 3.19: The RA module functioning.

Providing personalization and adaptation

Adaptation, personalization, alarm triggering, and control over environment are handled with a rule-based approach [142] that relies on a suitable language, namely ATML [143]. ATML is compliant with RuleML in the sense that most of ATML definitions rely on the RuleML definitions.

A trigger in ATML is described by its *name* – in order to distinguish it from the overall set of triggers– and a set of *properties* – each one incorporating different attributes helping to understand how to interact with the rule. Moreover, a rule defines the implications of its action through two main subsections: *head* and body. *Head* is used to define the actions (*TriggerAction*) to be executed whenever the condition of the rule is met. Every *TriggerAction* is defined by a single action to be performed when a given condition (defined in the body section) is met. A *TriggerAction* is defined through three tags: *op*, which indicates the command to be performed on the target; *who*, which describes which system performs the operation; and *device*, which defines the targeted appliance. *Body* expresses the condition of the rule by means of comparison and logic operation.

A knowledge representation of the context which needs to be captured and stored, from the different data sources and adopted devices, has been devised. The outcome of the context formalization is depicted in Figure 3.20, in which the different context component are presented. This definition incorporates different categories taken into account when evaluating the context:

- Time: representing the current moment taking place.
- Environment: referring to direct information of the context depending on environmental measures.
- Habits: providing information about physiological measurements and normal activities.
- Device: representing the status of the devices controlled by the system.

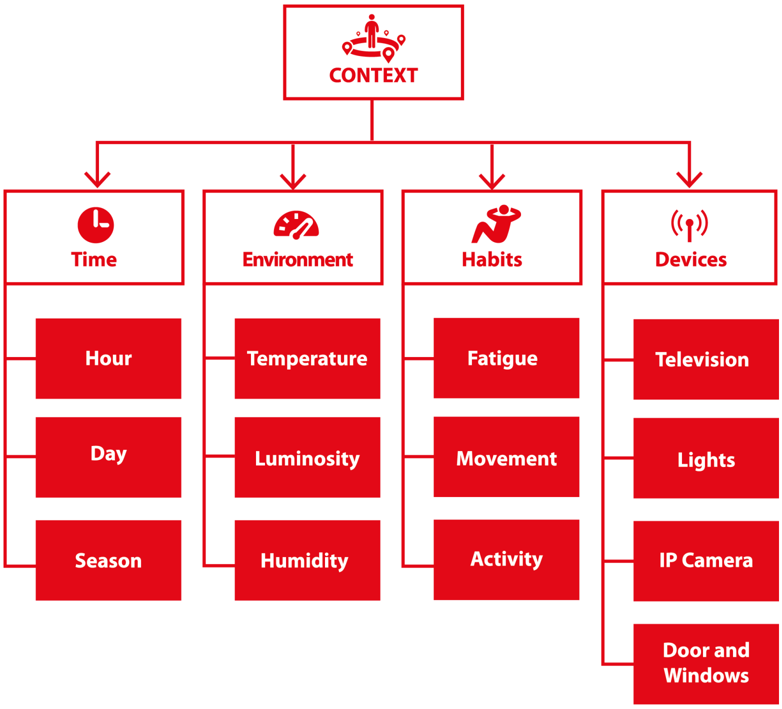

FIGURE 3.20: Context definition.

To perform personalization and adaptation we rely on machine learning techniques able to infer the behavioral patterns of the system, to learn user's habits and to adapt according to user's preferences.

3.4.4 The Therapist station

A Web application called the Therapist Station[10] (see Figure 3.21[11]) provides therapists/clinicians the ability to manage their clients remotely, assign cognitive rehabilitation tasks, undertake quality-of-life assessment, and enhance communication between therapist and the end-user using the BCI.

The Therapist Station receives notifications, summaries, statistics, and general information belonging to the users through a web application. Its goal is to keep informed therapists and caregivers about emergencies as soon as they happen and to proactively inform them about changes in user habits and/or to perform some therapy. In this way, therapists and caregivers become aware of user context by acquiring heterogeneous data coming from sensors and other sources.

The Therapy Station has been implemented as a Web-based application and provides user management, rehabilitation task management, therapy assessment, rule definition, statistics on system usage, as well as for communication between therapists and user.

A modular approach was considered from the very starting point of the Therapy Station design, which led to the definition of a loosely coupled system where each of

[10]https://station.backhome-fp7.eu:8443/BackHome/
[11]For the sake of anonymity, the real name has been ommitted an the user has been named "HU1 Cedar"

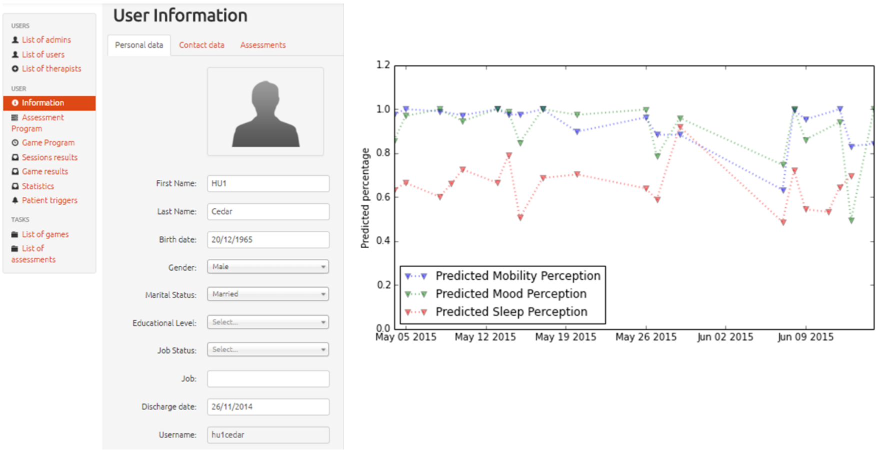

FIGURE 3.21: The Therapist Station: user management, illustrated with a sample form to update the information of a particular user (on the left) and results of quality of life assessment, in terms of predicted mobility, sleeping, and mood (on the right).

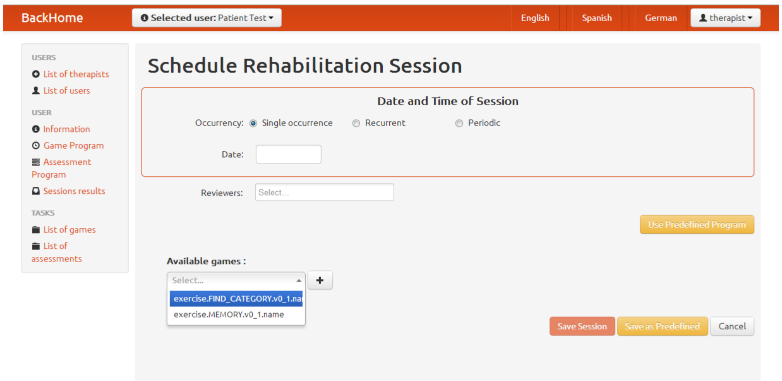

FIGURE 3.22: Scheduling cognitive rehabilitation tasks through the Therapist Station.

its components keeps its logic as self-contained as possible [147]. This design strategy is crucial in order to manage changes while reducing its overall impact in the rest of the platform. As a result, each of the main functionality is encapsulated in a self-contained module, which in turn, is managed by the platform infrastructure services. Those base infrastructure services are in charge of the definition of a common application context where every module is registered while providing cross-platform functionality as well.

Analogously to previous key innovations i) to iv), to our best knowledge, such therapist station connected to a BCI multifunctional system has not been implemented before, and we have labeled it as our key innovation v). Therapists are able to interact with the users remotely in real time or asynchronously and monitor the use of the BCI-based AT, the outcomes of the cognitive rehabilitation tasks and the assessment of quality-of-life. It enables the therapist to plan, schedule, telemonitor and personalize the prescription of cognitive rehabilitation tasks and quality-of-life questionnaires using the therapist station and to motivate the users to carry out those tasks inside their therapeutic range (i.e. supporting their progress), in order to help them to attain beneficial therapeutic results.

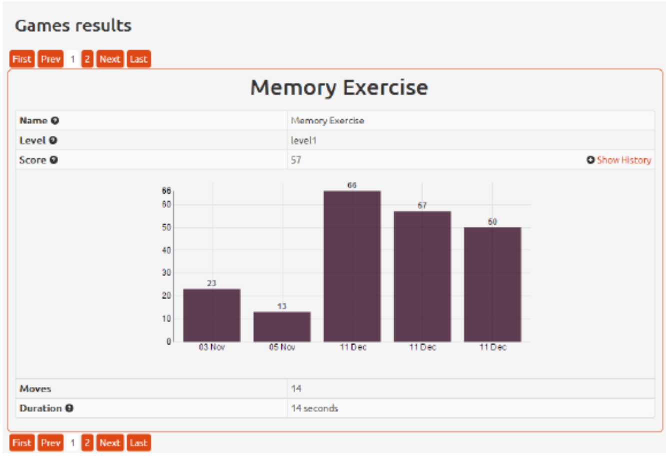

FIGURE 3.23: Therapist station - Results of the memory-card task.

As for the cognitive rehabilitation sessions, using the Therapist Station, healthcare professionals can remotely manage a caseload of people recently discharged from acute care. They can prescribe and review rehabilitation sessions (see Figure 3.22). Through the Therapist Station, game sessions can be configured, setting the type of games that the user will execute, their order in the session and the difficulty level and specific parameters for each one of them. Additionally, the Therapist Station allows healthcare professionals to establish an occurrence pattern for the session along the time. If the same session must be executed several times, professionals can set the type of occurrence and its pattern to make the session occur at programmed times in the future. Once the session is scheduled, users will see their BCI matrix updated on the User Station the day the session is scheduled. Through that icon, the user will start the session. The user can then execute all the games contained in it in consecutive order. Upon completion of the game session execution on User Station, results are sent back to the Therapist Station for review. At this point, those healthcare professionals involved in the session –the prescriber and the specified reviewers– are notified with an alert in the Therapist Station dashboard indicating that the user has completed the session. Healthcare professionals with the right credentials can browse user session results once they are received. The Therapist Station provides a session results view and an overview of completed sessions to map progress, which shows session parameters and statistics along the specific results (see Figure 3.23).

One of the goals of the sensor-based system is to automatically assess quality of life of the users. Accordingly, results and statistics are sent to the Therapist Station in order to inform the therapist about improvement/worsening of user's quality of life [12]. Moreover, the therapist may directly ask the user to fill a questionnaire. The therapist can decide the occurrence of quality-of-life questionnaire filling and, once scheduled, the user receives an update in the BCI matrix. Once the user, with the help of the caregiver, has filled the questionnaire, results are sent to the therapist that may revise them.

Furthermore, through the Therapist Station, therapists may consult a summary of activities performed at home by the user; e.g., visited rooms, sleeping hours and time elapsed at home. Thanks to the IM, the Therapist Station daily receives the summary of the information regarding the daily-life activities of the user (computed by SC). Figure

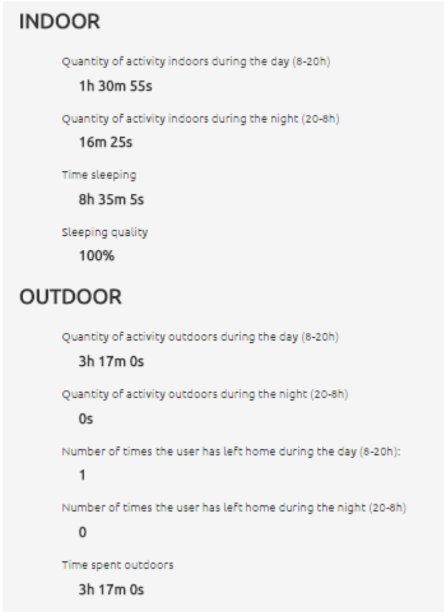

FIGURE 3.24: An example of QoL data inferred from the sensors' data as shown to the therapist.

3.24 shows an example of data coming from the sensors regarding both indoor and outdoor activities.

FIGURE 3.25: Interface for storing the performed actions at the User Station.

Figure 3.25 shows how the BCI usage is also monitored and high-level statistics provided. This information includes BCI session duration, setup time and training time as well as the number of selections, the average elapsed time per selection and a breakdown of the status of the session selections. Figure 3.26 shows how therapists have the ability to browse the full list of selections executed by a user, such as context information as application running, selected value, grid size and selected position, among other statistics around the BCI usage by the end user.

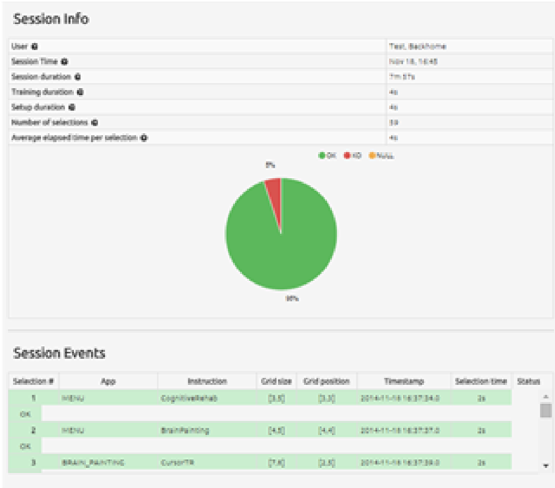

FIGURE 3.26: BCI Statistics interface at the Therapist Station.

Moreover, the therapist can define rules in order to be alerted in case some anomalies are detected. For instance, let us consider the case the therapist is interested in tracking the sleeping pattern. In fact, since BackHome real end-users have a very severe disability, they may feel depressed.

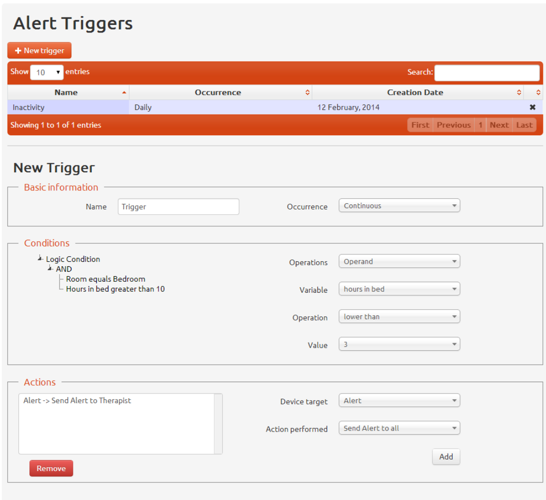

FIGURE 3.27: Therapist Interface for trigger definition.

Thus, detecting how much time the user is sleeping can help the therapist detect a depression at an early stage of the disease. To this end, the therapist may set a rule to raise an alarm if the user spends more than ten hours at bed in a day. Figure 3.27 shows the interface through which the therapist may define a rule. We have previously learned in Figure 3.19 how these rules are internally in language ATML and eventually stored and executed as DROOLS rules in the KBR .The system controls the sleep pattern of user to detects abnormal situations. In so doing, if the user has been at bed for more than ten hours and the user station detects it, an alert is raised to the therapist who receives a message at the dashboard of the system showing the alert that has been triggered and the user who is involved. After receiving the alert, the therapist contacts with user's caregiver in order to know the reason of this situation.

Chapter 4

Testing and validation with end users

4.1 Introduction

We have described in detail the BackHome system in previous Chapter 3 and in particular, Section 3.4.3 of Chapter 3 describes in detail the BackHome TMHSS.

The BackHome system is the result of a 3 years long UCD process which involved iterative testing with many users of all kinds, which the section 4.3.1 presents as the first main result. Next, section 4.3.2 presents the results of the evaluation of the overall BackHome system and its good acceptance by end-users at home, caregivers and therapists. Previously, Section 4.2 presents the validation methods employed in the final tests with the end-users at their own homes in Belfast.

The TMHSS of the BackHome system has been firstly tested in 2 young able-bodied users' homes and 8 elderly able-bodied users' homes in Barcelona. On one hand, Section 4.3.3 shows how those tests have helped to evaluate the potential and improve the ability of the TMHSS to recognize users' activities. On the other hand, Section 4.3.4 demonstrates the potential of the TMHSS to automatically and remotely assess QoL of individuals. Subsequently, the TMHSS has been integrated in the overall BackHome system and, thus, installed at the 4 end-user's homes in Belfast. Results concerning the 6 weeks of TMHSS testing in Belfast are then reported in Section 4.3.5.

4.2 End-user validation methods

A total of 4 participants were recruited for the six-week home based evaluation of the system. For the sake of anonymity they will be referred as Home User 1 (HU1), Home User 2 (HU2), Home User 3 (HU3), and Home User 4 (HU4). Only two of the participants concluded the six-week evaluation period. Attempts to set up and keep the system up and running for the 6 weeks in HU2's home failed due to unstable Internet connection and other basic technological barriers of his residential setting with shared resources; whereas HU4 became ill after the installation of the BCI and did not recover in time to participate in the home based testing. Thus, the final evaluation has only been successfully performed from beginning to end with HU1 and HU3, which is illustrated in Figure 4.1. Again, we need to emphasize that the high cost of equipment, especially BCI, and the uniqueness of the target end user at home (severe disabled people), has limited the number of end users in the final experiment.

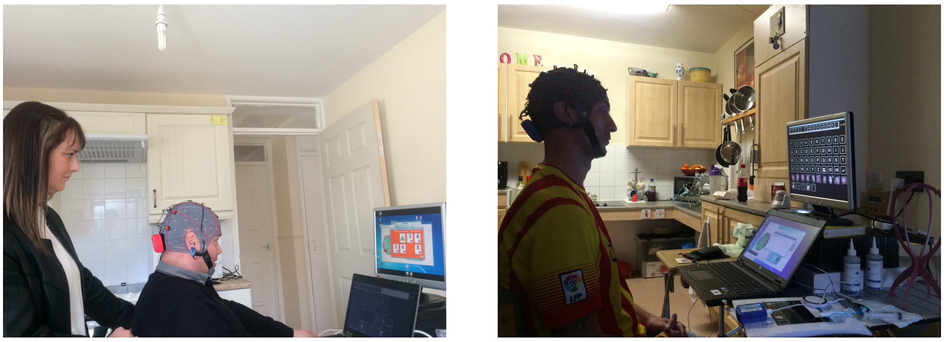

FIGURE 4.1: End-users at their homes: Home User 1 (HU1, on the right) and Home User 3 (HU3, on the left) using the system.

HU1 and HU3 are 50 and 37 years old, respectively. They experienced a severe brain injury as a result of a car accident (in 2001, HU1, and in 2004, HU3), both of them are currently living in the community post acute service rehabilitation, and have been involved in the BackHome UCD process from the beginning. They had no previous experience of BCI prior to the project. The sensors were installed in their home, Moves was downloaded onto their smartphone. They answered the questionnaire needed to test the telemonitoring system each day. HU1 used a g.Nautilus with 8 gel electrodes that were fixed in a medium size cap; whereas HU3 used a gel based g.Nautilus with 32 gel electrodes that were fixed in a medium size cap. In both cases,the data from the eight channels (Fz, Cz, Pz, P3, P4, PO7, PO8, Oz) along with a reference attached to the right ear and a ground at FPz, was amplified by a waterproof device with contactless charging attached by velcro to the back of the cap and the signals were wirelessly transmitted to the base station. In order to support the HU3's non-expert caregiver, the 8 electrodes that required gel were highlighted on the cap with a small strip of brown tape.

The laptop recording the data and displaying all of the BCI's applications was placed in front of both users. A computer stand was placed behind the laptop to support the external monitor to be visible above the laptop. The P300 matrix was visible on the laptop and the external monitor displayed the systems applications. The BCI user interface was configured in both cases like this: 120 ms. for the display time of the famous faces icons, 80 ms. for the time in between flashes, and 10 for the number of flashes before a selection (those parameters were selected independently in both cases following user preferences at setup time, and only by chance they resulted to bring the same values).

A training session on the set up of the BCI using gel based electrodes was run for the 4 caregivers[1] The session involved a thorough explanation of their role in the validation process and a step-by-step demonstration of how to set up the system and the functionality of each application. Each attendee then got the opportunity to set up a user on the system. The caregivers received an easy to use manual to support them during the evaluation. At least two additional training sessions were undertaken when the system was deployed into the participant's home and shadowing sessions were completed.

[1]For the sake of anonymity they will be referred as Caregiver 1 (CG1), Caregiver 2 (CG2), Caregiver 3 (CG3), and Caregiver 4 (CG4).

A folder was given to each home user and caregiver to outline their tasks and support them through the 6 weeks of testing. Each week the end-user was asked to complete at least three tasks: 1 set task to demonstrate use on one aspect of the system, 1 cognitive rehabilitation task sent to the user via the therapist station and 1 free usage task where users could do anything they liked. End-users specified their preferred tasks during testing of the previous iteration of the prototype and these were incorporated into the set tasks. The set tasks were; tweeting BCI at home, viewing a clip on YouTube, using the multimedia player, posting a comment on Facebook about the weather, Google the search term BCI, perform cognitive rehabilitation sessions attempting each of the three tasks (starting at level 1 and increasing to level 2 and 3) and create a picture using the Brain Painting application. The task was deemed complete when each step that had been set out by the research team was performed on the system and this was self-reported by the end-user/caregiver.

Several meetings were organized with specialist professional groups to gather perspectives on the BackHome therapist station and to identify its usability in a real life setting. The professionals involved in this evaluation were primarily occupational therapists (N=44). Other healthcare professionals included psychologists (N=3), speech and language therapist's (N=2), physiotherapist's (N=2), a social worker (N=1) and a nurse (N=1).

4.3 Results

Results are next presented following the structure of 5 research questions and contributions introduced in Chapter 1:

- User Centered Design of a multifunctional BCI
- Acceptance of BCI-based AT by end users at home
- Activity recognition with the TMHSS
- Context-aware QoL telemonitoring
- Telemonitoring severely disabled people

4.3.1 User Centered Design of a multifunctional BCI

The novel BackHome system offers individuals with disabilities a range of useful services available via brain-computer interfaces (BCIs), to help restore their independence. This is the time such technology is ready to be deployed in the real world, i.e., at the target end users' home. This has been achieved by the development of practical electrodes, easy to use software and delivering telemonitoring and home support capabilities which have been conceived, implemented and tested within a User Centered Design (UCD) approach. The final BackHome system is the result of a 3 years long process involving extensive user engagement to maximize effectiveness, reliability, robustness and ease of use of a home based BCI system. The system is comprised of ergonomic and hassle-free BCI equipment; one-click software services for smart home control, cognitive stimulation and Web browsing; and remote telemonitoring and home support tools to enable independent home use for non-expert carers and users. The details of the UCD approach and the resulting BackHome system have been presented extensively in previous Chapter 3, which we will wrap up with a summary here.

The development and validation of BackHome has gone through three main iterative stages of design and work directly with target end users, i.e. people with disability of neurological origin and therapists working in neurology. In preparation for the installation of the system at the end users' homes for long term evaluation of half a year, a pre-evaluation phase of the services in the overall system was undertaken by a control group of fourteen healthy users (9 females, M = 28.1 years ± 8.6, range: 21-46) [110]. Subsequently a total of nine end-users, four users with muscle impairments (f, 80 years; f, 58 years; m, 42 years; m, 51 years) and five users (1 female, M = 37 years, ± 8.7) who are living with acquired brain injury (Post ABI M = 9.8 yrs, ± 3.7) operated the system. All of them completed the protocol on three different occasions. Seven of the nine end users involved in the evaluation were able to gain control over the BCI and achieved satisfactory accuracies. Among the end-users with muscle impairments, one achieved scores in advance of >90 % accuracy for the spelling, games and twitter tasks. Another achieved lower accuracies scores averaging 75 %. Two of the initial four end-users undertaking the evaluation were unable to operate the BCI on one occasion. One end user had difficulty focusing on the relatively small symbols in the control matrices and the second had significant muscle spasticity that caused artifacts in the signal. The extended evaluation with end-users with acquired brain injury recorded an average accuracy score of 76 % across the four applications. The highest overall accuracy was achieved with the Speller (82.07 % ± 13.34) and the lowest with the 'control the camera' task (64 % ± 22.8).

4.3.2 Acceptance of BCI-based AT by end users at home

The BackHome system is a multi-functional BCI system, the final outcome of a UCD approach, whose ambition is to move BCI systems from laboratories into the home of people in need for their independent home use. The results of testing and evaluation of the BackHome system with end-users at their own homes, show good acceptance from end-users, caregivers and therapists, which reported promising usability levels, good user satisfaction and good levels of control in the use of services and home support based on remote monitoring tools[148].

End-users' satisfaction

At the end of the evaluation, end-users were asked to complete the NASA-TLX (NASA-Task Load Index by [149]), the eQUEST 2.0 (extended Quebec User Evaluation of Satisfaction with Assistive Technology by [121])[2] and a customized usability questionnaire. Results reported by HU1 ad HU3 are illustrated in Table 4.1. Both users reported satisfaction on the eQUEST 2.0 with a slightly lower satisfaction rating on the BCI specific added items. HU1 rated ease of use; effectiveness; and reliability as most important on eQUEST 2.0 and HU3 reported safety; speed; and reliability as the most important. HU1 reported on the eQUEST 2.0 that the wireless headset on the g.Nautilus *was the only way to have it* although the cap needs to be *more stylish*. In terms of the AT ease of use, he felt that the two screens *make it difficult to concentrate*. On the eQUEST 2.0, HU3 felt the ease of adjusting was *temperamental & inconsistent*, the ease of use was *inconsistent* and the speed was *sometimes good, sometimes not so good*. HU1 reported far higher workload on the NASA-TLX compared to HU3. HU1 reported feeling frustrated at times during the evaluation and this effort to control the system could be reflected in

[2] Range 1 = not satisfied at all to 5 = very satisfied

the NASA-TLX score. HU3 reported not feeling in control when operating the BCI on the usability questionnaire.

TABLE 4.1: Results from satisfaction questionnaires.

	HU1	HU3	Max. score
eQUEST 2.0 total score	4.15	4	5
eQUEST 2.0 added items	3.7	3.7	5
NASA-TLX	66.61	37	100
Did you feel in control, while using the system?	yes	no	n/a
Would you describe the system as intuitive?	yes	yes	n/a
Operating the interface was...	easy	easy	n/a
Did you like the symbols/icons of the interface?	yes	yes	n/a
Did you like the colours of the interface?	yes	yes	n/a

After each session was complete the therapist station would automatically open up on the laptop and ask the user to answer *How satisfied were you with the BCI session?* (with 10 being very satisfied and 0 is not satisfied) and *How would you estimate your level of control was over the BCI during the last session (did the BCI respond to the selections you wanted to make)* and the user was asked to selection from: High (100-90%); Medium (90-70%); Low (70-50%); Zero (50-0%). Additionally, following the set task and cognitive rehabilitation task the end-user was asked *Could you complete the task?* yes/ no.

The BCI system was set up in the kitchen of HU1's home (see Figure 4.1, left side). HU1 reported an average satisfaction of 6.81 ranging from 0 to 10 over the six-week evaluation (Figure 4.2, left side)[3]. The variation in satisfaction was linked to BCI performance according to the comments left on the therapist station *not a good session because of the inability for the system to be responsive*. HU1 had a mixture of positive and negative experiences ranging from *I had to make the selections twice on most occasions* to *Great session. Probably the best yet*. Additional, HU1's perceived level of control was medium and that the system responded to his desired commands *sometimes* to *mostly*. The caregiver supported the user to navigate the system and complete all but 4 tasks. They reported a satisfaction rate of 8.61 out of 10 with the set up of the system.

HU3 rated his satisfaction with the system at 5.84 out of 10 indicating he was *more or less satisfied* (see Figure 4.2, right side). He rated his level of control operating the BCI as *low* to *medium* and that the system responded to his desired commands *sometimes* to *mostly*. HU3 reported that activities of "Activity of Daily Living" level 2 was the only task for which he did not understand the commands. There also was difficulty when the *Twitter page would not come up*. HU3 enjoyed the experience when it was *very reactive* describing operating the BCI as *mentally rewarding* and *fun*.

During the six-week evaluation all of the set tasks, cognitive rehabilitation tasks and free usage tasks were attempted by HU1. HU1 was able to successfully complete 72%

[3] The 0 scores on May 1 and May 30 were set by error and were excluded from the average score.

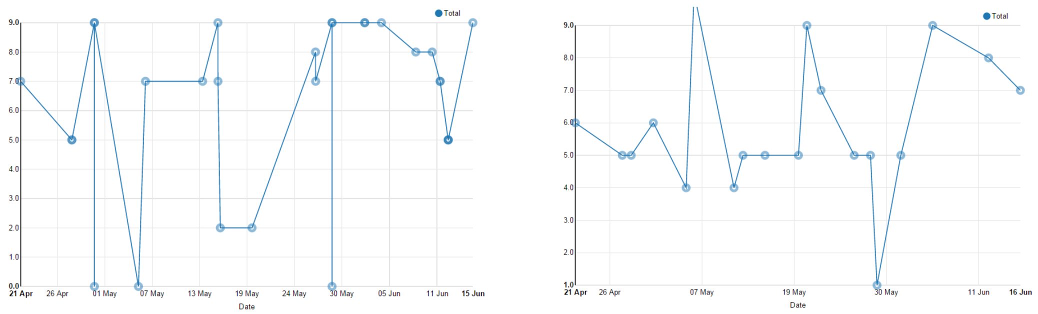

FIGURE 4.2: HU1 (on the left): BCI satisfaction = 6.81 - Rate of Control = medium (2.06). HU3 (on the right): BCI satisfaction = 5.84 - Rate of Control = low to medium (1.4).

(13 out of the 18) of the tasks set out by the research team. The reported reason for not completing the tasks was the inability to make a selection due to frequency of suppressed selections. This means that the threshold for the system to make a selection was not reached so a selection was not made and the flashing continued. The caregivers recorded the various applications explored during the free usage sessions, which were Google searches, using the multimedia player, social media, YouTube and controlling home environment. It is inferred that a number of other activities were undertaken on the BCI as 5 additional cognitive rehabilitation sessions were found on the therapist station having been completed during the evaluation but were not accounted for within the folder. HU1 reported that the web tags to make selection were placed over the text field he was trying to type into obscuring his view.

HU3 lived in an apartment and the BCI system was set up in the living area that was connected to his kitchen (see Figure 4.1, right side). HU3 was able to complete 61% (11 of the 18) of the tasks completely during the six-week evaluation. The caregiver recorded the tasks which end-users tried to complete during free usage, which included free spelling, cognitive rehabilitation, social media, YouTube, BrainPainting, and interacting with his home environment. In keeping with the experiences of HU1, HU3 completed 6 additional cognitive rehabilitation tasks during the evaluation that were not reported by the caregiver but were recorded on the therapist station.

Caregivers' satisfaction

The 4 caregivers were required to set up the end-user to operate the BCI on three occasions during each of the six weeks and complete a daily set up questionnaire after each of the 18 sessions.

After the training sessions, and after the six weeks home testing, caregivers were also asked to complete a satisfaction questionnaire; Table 4.2 depicts the questionnaire and the summary of results.

TABLE 4.2: The caregivers' satisfaction questionnaire.

	Do you feel confident operating the system without support?	**What did you like about the system?**	**What do you not like about the system?**	**Could anything be done to make this system easier to use on a regular base**
CG1	Yes: "Familiarity and experience made it easier to deal with any technical issues as the testing progressed"	"When users where able to complete tasks quickly it gave them great satisfaction."	"It was inconsistent. I would prefer a system that looks longer to set up but was more reliable and responded more quickly during tasks."	"A totally immersible cap would make the cleaning easier".
CG2	Yes: "As the weeks have went by I have got more confident and do feel like I can operate without support"	"Seeing the difference it can make to someone's life"	"The issues with connection to amplifier"	"Just a more reliable connection to enable ease of set up"
CG3	Yes	"The ease of setting and sense of achievement"	N/A	"It is just the time constraint within the unit makes this difficult"

Therapists' satisfaction

A protocol was defined to test the Therapist Station in dedicated focus group sessions (Figure 4.3) which involved the following groups of tasks: user management; user assessment; Cognitive Rehabilitation scheduling; BCI usage statistics; and triggers configuration. After following the protocol, therapists were asked to fill a questionnaire composed of 43 questions about all the actions performed during the testing.

A total of N= 50 therapists felt the BackHome system could benefit their clients and equally, N=50 believed the BackHome system could benefit their day-to-day practice. The functionality, usability, and application to practice were aspects of the system that therapists liked. In particular, the "measures of progress", "cognitive rehabilitation" and "quality of life measures" were particularly useful for therapists. There were a number of suggestions made during the evaluation. Overall the therapist station was viewed in a positive light and considered to be an asset to daily practice. On average, the 36.63% of the therapists evaluated as positive (4) the overall platform and the 44.22% as very positive (5), making a total of 80.86% of positive and very positive evaluation.

FIGURE 4.3: Therapists using the therapist station on iPads

4.3.3 Activity recognition with the TMHSS

The Activity Recognition (AR) module of the TMHSS described in Section 3.4.3 needs to provide precise information about the activities and habits of the user. This is one of the primary outputs to the users of such TMHSS, but besides that the AR must provide reliable inputs to the following modules (Event Notification - EN, Summary Computation - SC, which provides QoL assessment among other outputs, and Risk Advisement - RA) for those modules to provide the right elaborated knowledge and trigger the right alerts. However, we have learned that sensors are wireless, binary, cheap, non intrusive and therefore noisy and error-prone.

In order to solve these limitations with the final goal of improving the overall performance of TMHSS, we have learned we are proposing an approach based on machine learning techniques [70] [150]. In this initial solution, we only consider motion and door sensors. The intelligent monitoring (IM) system continuously and concurrently listens for new data in a given window, according to a sliding window approach [151]. For each window, data are pre-processed and analyzed. As an example, let us consider the Figure 4.4 where once the current window recognizes a door event at time tb, it looks for the previous one in the window or before (in the example ta). Then, the period between those door events (i.e, $ta - tb$) is classified by the hierarchical classifier. Seemly, when the event tc has been recognized, the period from tb to tc is classified. Finally, the period from tc to the end of the window is classified. In case of no door events have been recognized, the period from ta to the end of the window is classified.

Let's recall the hierarchical approach used in the module AR and depicted in Figure 3.17 of Section 3.4.3 above, which is composed of two levels. The upper is aimed at recognizing if the user is at home or not, whereas the lower is aimed at recognizing if the user is alone or received some visit:

- *Is the user at home?* The goal of the classifier at the upper level is to improve performance of the door sensor. In fact, it may happen that the sensor registers a status change (from closed to open) even if the door has not been opened. This implies that the TMHSS may register that the user is away and, in the meanwhile, activities are detected at user's home. On the contrary, the TMHSS may register that the user is at home and, in the meanwhile, activities are not detected at user's

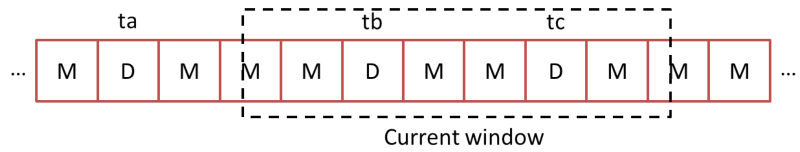

FIGURE 4.4: An example of the sliding window approach, where M means "motion event" and D means "door event"

home. To solve, or at least reduce, this problem, we built a supervised classifier able to recognize if the door sensor is working well or erroneous events have been detected. First, we revised the data gathered by the TMHSS searching for anomalies, i.e.: (1) the user is away and at home some events are detected and (2) the user is at home and no events are detected. Then, we validated those data by relying on Moves, installed and running on the user smartphone. In fact, Moves, among other functionality, is able to localize the user. Hence, using Moves as an "oracle" we build a dataset in which each entry is labeled depending on the fact that the door sensor was right (label "1") or wrong (label "0").

- *Is the user alone?* The goal of the classifier at the lower level is to identify whether the user is alone or not. The input data of this classifier are those that has been filtered by the upper level, being recognized as positives. To build this classifier, we rely on the novelty detection approach [146] used when data has few positive cases (i.e., anomalies) compared with the negatives (i.e., regular cases); in case of skewed data. In particular, we rely on the approach presented in [152] that tries to estimate a function f that is positive on the dataset and negative on the complement. The functional form of f is given by a kernel expansion in terms of a potentially small subset of the training data; it is regularized by controlling the length of the weight vector in an associated feature space. The expansion coefficients are found by solving a quadratic programming problem, which we do by carrying out sequential optimization over pairs of input patterns.

First we evaluated this approach for activity recognition with 1 able-bodied in Barcelona ("Control User", shortly CU). According to the user's home plan, the following sensors were been installed: 1 door sensor; 4 presence sensors (1 living room, 1 bedroom, 1 kitchen, 1 bathroom); and 3 switch and power meters (1 PC, 1 Nintendo WII, 1 kettle). A useful interface allows technicians to remotely view, manage and/or change the configuration of the TMHSS and to have a view of the collected data, when needed (see Figure 4.5).

To validate the performance of the system, we carried out a preliminary 1 month experiment to recognize indoor habits [69]. Preliminary results showed that we could distinguish three different types of routines depending on the type of day: workday, part-time workday and weekend. Results show that it is possible to note changes in the habits of the user depending on the day of the week. In particular, it could be identified the hours in which the user is at home and the room(s) in which passes the majority of the time. Figure 4.6 and Figure 4.7 show an example of recognized habits for a full-time workday (i.e., Monday) and a part-time workday (i.e., Friday), respectively.

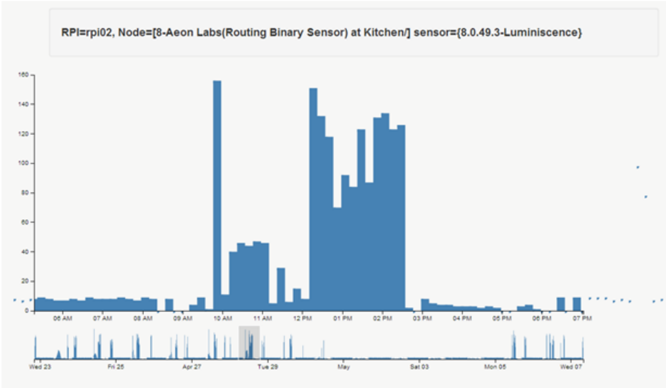

FIGURE 4.5: Remote check of luminescence status of a particular sensor.

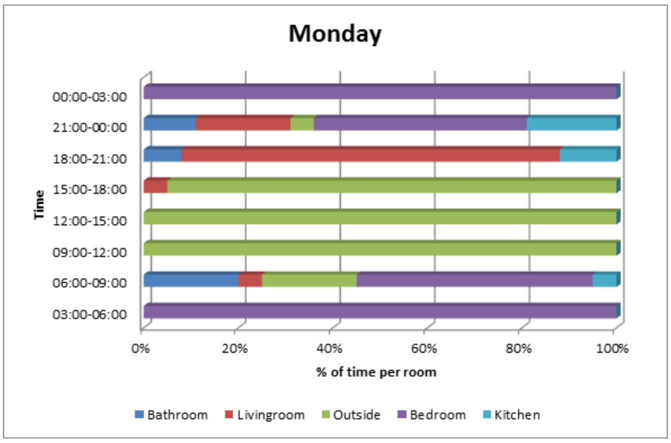

FIGURE 4.6: Control User's habits: full-time workday.

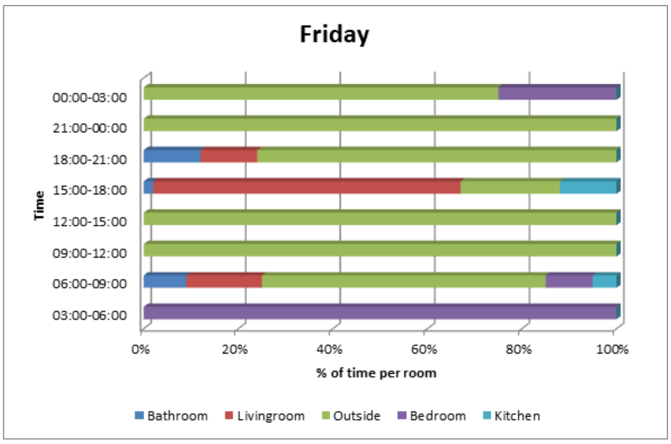

FIGURE 4.7: Control User's habits: part-time workday.

After this preliminary check-up testing, in order to train and test the proposed hierarchical approach, we considered a window of 4 months for training and evaluation (training dataset) and a window of 1 month for the test (testing dataset). Experiments were performed at each level of the hierarchy. First, we performed experiments to identify the best supervised classifier to be used at the upper level of the hierarchy. Subsequently, we applied the novelty detection algorithm on the data filtered by the classifier at the upper level, to validate the classifier at the lower one. Finally, we measured the performance of the overall approach.

Once this first testing was done with promising results, we installed the TMHSS in 8 elderly people's homes for evaluation and testing for a total of 41 days [150].

Experimental results with the Control User

Is the user at home? First of all, we built the training dataset with door events (gathered by the door sensor) in a window of 4 months. Those data were then validated by relying on the information coming from Moves. The entries were manually labeled in two classes *Correct data* and *User not at home* according to the following criteria:

- *Correct data*: 0 if the data gathered from the door sensor differs from the data gathered from Moves; 1 otherwise.
- *User not at home*: 0 if the user is at home; 1 otherwise.

First, we defined and implemented a rule-based system to verify if an approach based on rules might help in improving the overall performance. The results coming from the rule-based system were then compared with those manually validated using Moves. Unfortunately, results showed a very few improvement with an accuracy of 77%. Thus, we decided to implement a supervised classifier.

The data labeled as 1 for the class *Correct data* were used to extract 8 different features using different combinations of the number of motion events in relation to door events. The dataset was then used to train four well-representative and successful families of supervised classifiers [153]: a Logistic Regression (LR) classifier, a Support Vector Machine (SVM), a Random-Forest (RF) and an AdaBoost (AB).

The dataset was divided in a training and an evaluation set and a 10-fold cross-validation method was used. The classifiers were then tested with an independent dataset. Table 4.3 shows results during the training phase and evaluation phase. As shown, the best performance was obtained by relying on the SVM (with $\gamma = 1.0$ and $C = 0.452$).

The best classifier was then used with the testing dataset and, on average, it obtained a F_1 of 0.97 and an accuracy of 0.968. Finally, it showed an improvement of 20% with respect to the rule-based approach.

Is the user alone? The data filtered by the classifier at the upper level, belonging to the monitored window of 4 months, were the training dataset of the classifier at the lower level. The corresponding dataset was composed by 57 normal instances (i.e., the user was alone) and 8 anomalies (i.e., the user received visits).

TABLE 4.3: Results for the high-level classifier during the training (T) and evaluation (E) phase.

Classifier	Parameter(s)	Accuracy (T)	Accuracy (E)
LR	$C = 0.005$	0.945 ± 0.09	0.885
SVM	$\gamma = 0.01, C = 1.0$	0.945 ± 0.09	0.885
SVM	$\gamma = 1.0, C = 0.452$	0.853 ± 0.12	0.943
SVM	$\gamma = 0.05, C = 0.452$	0.930 ± 0.11	0.885
SVM	$\gamma = 0.01, C = 0.257$	0.945 ± 0.09	0.885
RF	$n\_estimators = 5$	0.943 ± 0.09	0.942
RF	$max\_features = 12$	0.930 ± 0.09	0.942
AB	$n\_estimators = 15$	0.918 ± 0.10	0.823

First of all, also in this case, we defined and implemented a rule-based classifier to verify if a rule-based approach could solve this problem. Since the rule-based approach is not able to correctly recognized anomalies, we used, also in this case, an SVM classifier (one-class SVM with RBF, non linear), extracting 8 features which in this case took into account only motion events. The classifier was trained by considering the normal instances and then evaluated introducing the anomalies. Table 4.4 shows the overall results.

TABLE 4.4: Results for the classifier at the lower level. The table reports the classification error calculated as the ratio between the number of detected anomalies and the number of instances in the dataset.

Parameter(s)	Error (T)
$\nu = 0.01, \gamma = 0.1$	0.0701
$\nu = 0.01, \gamma = 0.5$	0.0877
$\nu = 0.01, \gamma = 1$	0.1578
$\nu = 0.05, \gamma = 0.1$	0.0877
$\nu = 0.05, \gamma = 0.5$	0.0877
$\nu = 0.05, \gamma = 1$	0.1403
$\nu = 0.1, \gamma = 0.1$	0.1052
$\nu = 0.1, \gamma = 0.5$	0.1052
$\nu = 0.1, \gamma = 1$	0.1403
$\nu = 0.5, \gamma = 0.1$	0.4912
$\nu = 0.5, \gamma = 0.5$	0.5087
$\nu = 0.5, \gamma = 1$	0.4912

Results during the evaluation phase showed that the system was able to correctly recognize all the anomalies. According to the obtained results, we selected the classifier with the regularization parameter $(\nu) = 0.01$ and $\gamma = 0.1$. Similarly to the classifier at the upper level, the system was tested with the data coming from the 1-month window of monitored events. Results showed an average accuracy of 0.94.

Overall results. Once both classifiers were trained, we tested the performance of the overall approach with the testing dataset corresponding to a window of 1 month. We compared the overall results with those obtained by using the rule-based approach in both levels of the hierarchy. Results are shown in Table 4.5 and point out that the proposed approach outperforms the rule-based one with a significant improvement.

TABLE 4.5: Results of the overall hierarchical approach with respect to the rule-based approach.

Metric	Rule-based	Hierarchical	Improv.
Accuracy	0.80	0.95	15%
Precision	0.68	0.94	26%
Recall	0.71	0.91	20%
F_1	0.69	0.92	23%

Experimental results with elderly people

The TMHSS was installed in 8 homes of people over 65 years old. To test the hierarchical classifier, we asked all the users to daily answer to two questions: "how many times have you gone out of home today?" and "how many visits have you received today?". Results are showed in Table 4.6, moreover, Figure 4.8 shows the performance of the classifier at the lower level for each of the monitored users.

TABLE 4.6: Experimental results from the installation at 8 elderly users' homes.

Metric	Is the user at home?	Is the user alone?
Accuracy	0.95	0.68
Precision	0.98	0.64
Recall	0.98	0.74
F_1	0.98	0.68

Results show that the classifier at the upper level had very good performance, comparable with those calculated with data from CU. On the contrary, the classifier at the lower level is less accurate than the system working with CU data. This can be caused by multiple factors. For instance, habits of elderly people and CU might be different. In particular, during the monitored period, CU received very few visits whereas the elderly users received visits more or less daily (e.g., the cleaning lady). Moreover, elderly people might have different activity patterns at home from younger people, e.g., normally they move more slowly and tend to have long inactivity periods. Also, home and room configuration might affect the classifier performance, i.e., short distances between rooms are generating more measurements than in broader places.

4.3.4 Context-aware QoL telemonitoring

Let us recall here the Intelligent Monitoring (IM) system (Figure 3.15), described in Section 3.4.3 of previous Chapter 3, which is comprised of: PP, the pre-processing module to encode the data for the analysis; ED, the emergency detection module to notify, for instance, in case of smoke or gas leakage; AR, the activity recognition module to identify location, position, activity- and sleeping-status of the user; EN, the event notification module to inform when a new event has been detected; SC, the summary computation module to perform summaries from the data; and RA, the risk advisement module to notify risks at runtime.

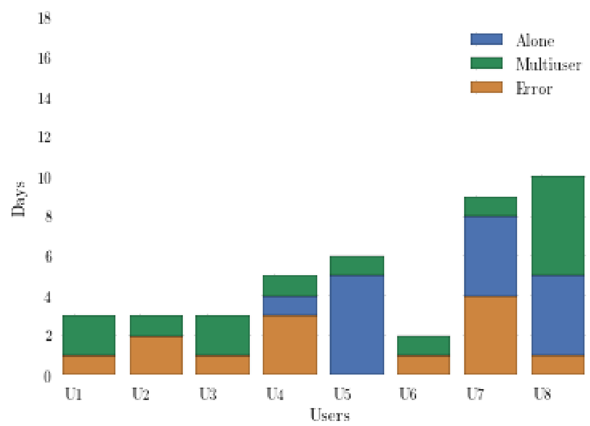

FIGURE 4.8: Results of the classifier at the lower level for each monitored user (U1 - U8).

The QoL assessment system is part of the SC module, which implements the methodology described in Chapter 2. It is composed of a set of sub-modules, each one devoted to assess a specific QoL item; namely: MOBILITY-assessment module; SLEEPING-assessment module; and MOOD-assessment module. Each sub-module is composed of two parts: Feature Extractor and Classifier. The Feature Extractor receives as input the list of notifications {n} coming from EN and the list of activities {a} from the AR and extracts the relevant features {f} to be given as input to the Classifier. The Classifier, then, uses those features to identify the right class Cl. This information will be then part of the overall summary $\sum$ provided as output by SC.

As stated in Section 1.4.4 above, three QoL items have been considered so far. Each Feature Extractor works with its proper list of features:

- MOBILITY: number of times the user left home, total time performing outdoor activities, total time performing activities (both indoors and outdoors), total time of inactivity, covered distance, number of performed steps, number of visited places, number of burned calories.
- SLEEPING: total sleeping time, hour the user went to sleep, hour the user woke up, number of times the user went to the toilet during the night, time spent at the toilet during the night, number of time the user went to the bedroom during the night, time spent at the bedroom during the night, number of sleeping hours the day before, number of sleeping hours in the five days before.
- MOOD: number of received visits, total time performing outdoor activities, total time performing activities (both indoors and outdoors), total time of inactivity, covered distance, number of performed steps, number of burned calories, hour the user went to sleep, hour the user woke up, number of times the user went to the toilet during the night, time spent at the toilet during the night, number of time the user went to the bedroom during the night, time spent at the bedroom during the night, number of sleeping hours the day before, number of sleeping hours in the five days before.

The Classifier is a supervised multi-class classifier built by using data previously labeled by the user and works on five classes, Very Bad, Bad, Normal, Good, and Very Good.

To evaluate the proposed methodology to automatically assess QoL, we used the data from one of the TMHSS installations in Barcelona, the only for which we could get enough data [145]. The selected user (SU) was an able-bodied young woman who lives alone. The habits of SU were monitored for 6 entire months. A total of about 80 days have been considered to build the dataset that has been labeled by using the answers given by SU to the following questionnaire, each question in a scale from 1 to 5:

- How was your ability to move about?
- How did you sleep last night?
- How was your mood?

Let us note that not all the monitored days were usable due to several reasons, such as user's vacations, visits received during the day (which don't allow to detect for example the number of visited rooms) or because the user didn't answer the labeling questionnaire.

The dataset was then divided in training-set and test-set and each classifier was then evaluated through a k-fold validation approach. Performance of 7 different techniques was compared in terms of F1 measure [154]: SVM, Logistic Regression, k-NN, Naïve Bayes, Decision Tree, Random Forest, and AdaBoost.

Mobility

A total of 82 labeled days were used to assess MOBILITY. Since the user labeled them as Normal (44 times), Good (32 times) and Very Good (6 times), only those three classes were considered to build the classifier.

Table 4.7 shows the results obtained during the testing phase; for each technique, the best configuration of parameters was reported. In particular, we tried the approach considering only data (i.e., features) from Moves (outdoor activities) and data from both Moves and the home-automation sensors (indoor and outdoor activities). As shown, in both configurations, SVM was the technique with best results. Moreover, the adoption of the home-automation sensors improved the performance.

The best classifiers were then used with the test-set obtaining a F1 of 0.569 considering only outdoor activities and a F1 of 0.654 in case of considering both indoor and outdoor activities. Those results show that adopting indoor sensors improved the overall performance highlighting the usefulness of the adopted sensor-based system.

Sleeping

A total of 84 labeled days were used to assess SLEEPING. The user labeled them as Bad (4 times), Normal (57 times), Good (23 times). Due to the small number of

TABLE 4.7: Results obtained in assessing MOBILITY during the training phase

Classifier	**Outdoor activities**		**Indoor and outdoor activities**	
	Params	**F1**	**Params**	**F1**
SVM	C = 1000 γ = 0.008	0.699	C = 1 γ = 0.04	0.765
Logistics regression	C = 1.693	0.662	C = 3.0	0.7645
kNN	k = 7	0.675	k = 3	0.684
Naïve Bayes	–	0.616	–	0.736
Decision tree	–	0.567	–	0.618
Random forest	estimators = 5	0.666	estimators = 100	0.700
AdaBoost	estimators = 50	0.620	estimators = 10	0.485

bad cases, we built different kinds of classifiers: 3-classes (Bad, Normal, Good), 2-classes-vs1 (Normal, Good), and 2-classes-vs2 (Bad&Normal, Good). Table 4.8 shows the results during the training phase. In this case, best results were obtained with a Random Forest approach in case of considering 3 classes and in case of considering only Normal and Good as classes. On the contrary, in case of considering together Bad and Normal, best results were obtained by adopting an SVM, like in case of MOBILITY.

TABLE 4.8: Results in assessing SLEEPING during the training phase

Classifier	**3-classes**		**2-classes-vs1**		**2-classes-vs2**	
	Params	**F1**	**Params**	**F1**	**Params**	**F1**
SVM	C = 50 γ = 0.1	0.630	C = 200 γ = 0.005	0.711	C = 15 γ = 0.08	0.722
Logistics Regression	C = 0.01	0.597	C = 0.04	0.703	C = 1.69	0.716
kNN	k = 11	0.572	k = 9	0.634	k = 7	0.645
Naïve Bayes	–	0.563	–	0.598	–	0.560
Decision tree	–	0.607	–	0.653	–	0.616
Random forest	estimators = 5	0.656	estimators = 150	0.727	estimators = 100	0.704
AdaBoost	estimators = 50	0.648	estimators = 50	0.677	estimators = 10	0.692

The best classifiers were then used with the test-set obtaining F1 of 0.654, 0.731, and 0.808, respectively. That means that the best solution consisted of considering Bad and Normal together. Of course, in case we got enough samples covering all the given classes new solutions should be investigated.

Mood

A total of 80 labeled days were used to assess MOOD. The user labeled them as Bad (1 time), Normal (44 times), Good (33 times), and Very Good (3 times). Due to answers given by the user, we decided to consider only 2 classes: Bad&Normal and Good&VeryGood. Moreover, we decided to perform experiments with all the features listed above as well as with a sub-set automatically selected.

Table 4.9 summarizes results obtained during the training phase. As shown, best results were obtained with a Random Forest considering a selected set of features. Nevertheless, during the test phase, best results were given by using the Random forest with all the features, obtaining a F1 = 0.739.

TABLE 4.9: Results obtained in assessing MOOD during the training phase

Classifier	All features		Selected features	
	Params	F1	Params	F1
SVM	C = 0.5 γ = 0.08	0.750	C = 100 γ = 0.002	0.776
Logistics Regression	C = 1.0	0.711	C = 9.0	0.776
kNN	k = 3	0.630	k = 3	0.759
Naïve Bayes	–	0.618	–	0.753
Decision tree	–	0.631	–	0.709
Random forest	estimators = 5	0.769	estimators = 100	0.814
AdaBoost	estimators = 50	0.711	estimators = 100	0.701

4.3.5 Telemonitoring severely disabled people

Eventually, the BackHome system with the integrated TMHSS was installed at 4 disabled end users' homes in Belfast, and the data collection and evaluation lasted 6 weeks.

Moving the system from a controlled environment to the end-user homes arose some problems, in particular for the data collection:

- HU1 user. Always answered 5 to the question regarding MOBILITY, therefore results achieved in the mobility experiments for this user cannot be considered relevant;
- HU2 user. This user dropped out during the testing session, thus we did not collect any data from him.
- HU3 user. This user did not use the Moves app therefore we did not include this user in the experiments for MOOD and MOBILITY. This user lives in a trusted environment so the user was not closing the door during the day so the system was not able to distinguish when he was at home or if he was with multiple people. Thus we did not include the data collected from this user in the QoL experiments.
- HU4 user. This user did not answer any questionnaire. Therefore this user was not included in the QoL experiments.

Similarly to the evaluation with the previous testing with able-bodied users, we first filtered out those days that were not valid according to a set of validation rules. Table 4.10 shows the final available data for experimentation:

TABLE 4.10: Data available for the experiment with disabled end-users

Users	Valid Questionnaires	Valid IM	Valid Moves	Available data
HU1	23	20	42	19 (sleep) 18 (mood, mobility)
HU3	30	5	0	0

The QoL system and its classifiers were built according to what has been described above. The dataset was divided into 2 independent datasets (train 70% and test 30%) and a set of regression methods were applied in order to learn from the training data. At the same time a set of parameters were applied in order to find the most accurate methods by means of a 5-cross validation framework.

Due to the little amount of available data, we studied three alternative strategies in order to build the most accurate methods:

- *Apply regression method of the control user.* This approach consisted on directly applying the regression methods of the control user over each test set of HU1.
- *Merging users' data.* This approach consisted on producing one regression method for each user. The data set would be composed by merging the data from the control user and from the particular end user.
- *Weighted merging data.* Another merging approach was proposed by weighting the instances from the end user and from the control user. The best final weights were computed by brute force and selecting the ones with better performance for the given user. Unfortunately this last approach did not worked out for the regression methods ela, lar, las and llr.

Mobility

On the evaluation stage described above, we concluded that using features extracted from the Moves app yielded better results. Therefore, the results presented here include only those days with collected data from the indoor monitoring and the Moves application.

Merging user's data, best results were obtained with {'svr_pol__degree': 2, 'svr_pol__C': 5}, the obtained best score being 0.33. The following values were obtained: Explained variance (r2 score): 0.0; Mean square error: 0.589305141329. Results are shown in Figure 4.9.

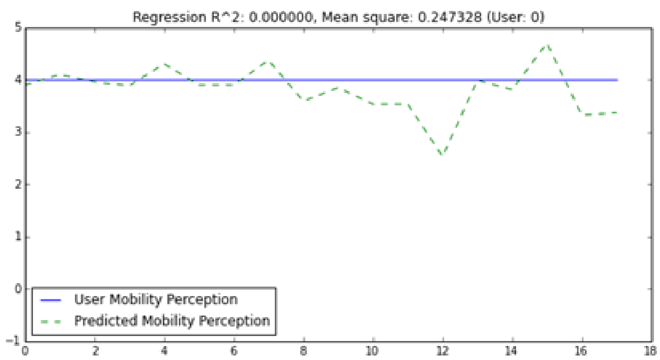

FIGURE 4.9: Results for MOBILITY merging user's data.

Sleeping

Merging users' data, the best results were obtained with the following configuration: {'rid__alpha': 36.061765077612336}, obtaining a score of 0.28. Results are shown in Figure 4.10.

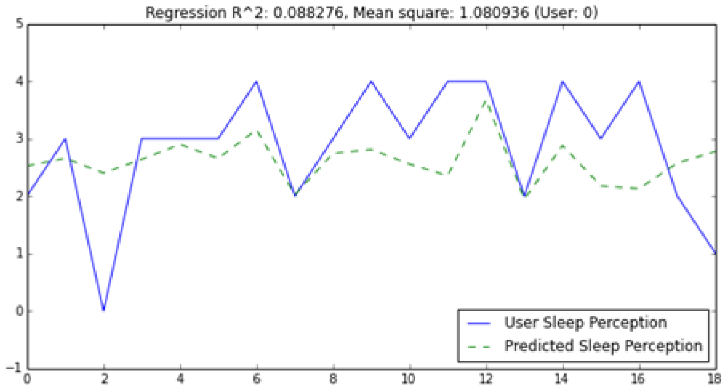

FIGURE 4.10: Results for SLEEPING for HU1 merging users' data.

Mood

Merging users' data, the best results (score of 0.51) were obtained with {'ela__alpha': 0.0010637648543163l3}. The corresponding values were: Explained variance (r2 score): 0.0; Mean square error: 1.06938401135. Results are shown in Figure 4.11.

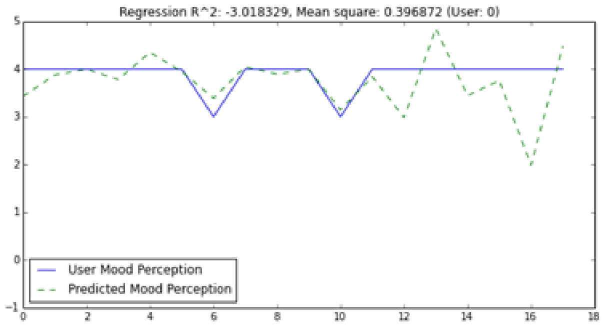

FIGURE 4.11: Results for MOOD of HU1 merging users' data.

Chapter 5

Discussion and impact

5.1 Discussion

In this Chapter we are presenting the discussion for the 5 research questions presented in Chapter 1, whose results have been displayed in Chapter 4. following the same structure here we are discussing about the 5 research questions and contributions:

- User Centered Design of a multifunctional BCI
- Acceptance of BCI-based AT by end users at home
- Activity recognition with the TMHSS
- Context-aware QoL telemonitoring
- Telemonitoring severely disabled people

5.1.1 User Centered Design of a multifunctional BCI

The BackHome system was designed according to a UCD approach, used for the first time throughout all development stages of a multi-functional BCI. This UCD approach involved training, deployment and evaluation by a significant number of users, both able-bodied and disabled and both in the laboratory and at home, the details have been described in detail in Chapter 3. Driven by that approach, the BackHome system achieved five key innovations: (i) an architecture able to meet the requirements of BCI multifunctionality and remote home support; (ii) a light, autonomous, comfortable and reliable BCI equipment; (iii) an easy-to-use software to control multifunctional applications; (iv) a telemonitoring and home support system for BCI independent use; and (v) a Therapist station to manage BCI-based remote services.

We decided to discard the integration of other research advances explored in the project lifetime such as a Multimodal Fatigue Support component, hybrid BCI capabilities (fusing different BCI paradigms like P300 and SSVEP in a single user interface) and a sliding keyword to make possible one screen user interface, because we considered they were not mature enough for real world deployment, but they will be further researched and might be eventually integrated in the future.

This BackHome system and the services provided make a significant contribution to enhance the opportunities for social inclusion and eHealth for people living with physical and cognitive impairment who would otherwise struggle to exert autonomy and independence in a world that is much more digitally enabled than ever before.

5.1.2 Acceptance of BCI-based AT by end users at home

To our knowledge, this is the first time a multi-functional BCI with such a wide range of services has been evaluated at home by end-users, also taking the therapists' and the non-expert caregivers' perspective into account. The two participants who fully completed the validation process at home were enthusiastic about their experience evaluating the BackHome system at their own home. Ultimately there were challenges; however the learning from this evaluation is essential to realize the fundamental goal of moving BCI into peoples' homes as an AT to support independent living. Home users were able to complete 61% and 72% of tasks set for them and also chosen by them over the six weeks. Satisfaction with the system was strongly linked to the systems responsiveness throughout the evaluation on the BCI satisfaction scale. Additionally, both home users were satisfied with the BCI as reflected in the eQUEST 2.0 questionnaire.

The system was innovative in hosting a wide range of applications for the user. It was evident from the evaluation that both home users enjoyed the cognitive rehabilitation tasks and the freedom of exploring all the different Web applications. The smaller matrix sizes proved to be more challenging to select and thus navigating through the menus to access the various applications could present a challenge. It was suggested to implement a pause button to stop the screen flashing. It was difficult to use; it needed to be selected twice to disable selections and selected two more times to enable selections again. Due to the high suppressed selection rate this required too much effort to operate. Additionally, a delay in the flashing was recommended in applications such as the web browser and cognitive rehabilitation to give the user an opportunity to decide on their next selection. The famous faces were a feature that users felt that supported their interaction with the BCI and one participant would have liked to use his family members' faces instead of celebrities.

The evaluation of caregiver satisfaction was essential because the caregiver is fundamental to the real world deployment of BCI systems, however there is little evidence of their important role in the literature. Essentially non-experts caregivers were able to support users at home and it was evident they were very motivated to support the completion of the tasks. The evaluation required extensive commitment from both the end-user and the caregiver due to the time obligations and patience needed when experiencing the technical challenges which is the nature of testing emerging technologies. A number of recommendations from the caregivers will endeavor to make BCI systems easier such as an even easier set up process, robust equipment for everyday use and a quicker process to set the end-user up. The evaluation is important to continue bridging the gap between engineer's perspectives of "easy set up" and the non-experts opinion.

Of course moving BCI technology from laboratories to end-users' homes brought very demanding issues which still need to be carefully addressed. This first phase of home based testing of any emerging technology is essential to identify how it can be operated in an uncontrolled environment and the unique experiences of people without expertise setting it up on an ongoing base. However, it is through these lessons and experiences that technology can be refined and made into a useful product.

The technological infrastructure needed to support a BCI system at home is important to consider. Our end-users are living within a supervised and supported living environment, which may be common for disabled people who could benefit from the use of BCI as an alternative AT. This is an important lesson as trend grows to develop ambitious technologies to enable people; it is essential that living environments can support the transition of complex technologies into real life settings.

Besides those minimum requirements, we will still need to address important improvements raised by end-users and caregivers. For example, the system was reported as very slow, and this was specially annoying when waiting for a change on the BCI mask when a smart home selection was done taking a minute or more because of the interoperation with an external module. So it is therefore crucial to enhance environmental control through BCI in the future. Implementing all the features of the BackHome system into one single screen instead of two would reduce the hardware necessary and would also make it easier for the user to interact with the system. The robustness of g.Nautilus is an area for future development as within a home environment with non-experts the wires in the cap became fragile and even broke. The aesthetic style of the cap could also be improved although becoming wireless was perceived as very satisfactory for the home users. As stated above, refining the dynamic stopping method to accurately execute suppressed selections only when the end-user is not interacting with the BCI matrix, will dramatically improve responsiveness of the system, perceived control by end-users, overall accuracy and performance and ultimately user satisfaction.

As a matter of fact, results about independent home evaluation of the BackHome system show a good acceptance of the system by both home users and caregivers. We need to acknowledge that although the system has been tested by many able-bodied and disabled users throughout the entire project life-cycle, only two end-users out of four succeeded to test the final system at their own home. The many technical, ethical, and economic logistics needed for such a complex real world evaluation prevented a broader testing, which will need to be done in the future.

5.1.3 Activity recognition with the TMHSS

Community based living, often alone with intermittent care, creates possible scenarios of risks for all individuals. When cognitive changes are likely to have taken place it is crucial to understand what the risks may be and monitor these. To monitor users' activity and habits at home, we are using our TMHSS which is able to gather data and report on the stability and evolution of the user's daily life activity. Unfortunately, performance of sensor-based TMHSS depends, among other issues, on the reliability of the adopted sensors. It is particularly true in the case of wireless and binary sensors being adopted. To solve this problem, we have presented a hierarchical approach, based on machine learning techniques, aimed at improving the recognition of the presence of the user at home and, being interested in monitoring people that live alone, if the user is alone or received some visits. Results with the Control User clearly showed a high discriminative performance improvement of 15% with respect to a rule-based solution.

To test the approach in the field, the system was installed in 8 elderly people's homes in Barcelona. Results confirmed the effectiveness of the system, especially on detecting home user presence and its absence, and, at the same time, highlight the need of some improvements in order to reach the same results obtained with the Control User. In particular, we envisage three main directions that may be gone through in the future: (i) to train the system with more data and to use a different approach for the classifier at the lower level, as for instance an ensemble of novelty detection algorithms; (ii) to train the system with data from elderly people instead of selecting a younger user as Control User; and (iii) to personalize the classifier for each user, i.e, to have a different system for each user, trained with data coming from the users themselves.

5.1.4 Context-aware QoL telemonitoring

Results presented in Section 4.3.4 of Chapter 4 showed that 3 quality-of-life items (namely, MOBILITY, SLEEPING, and MOOD) could be inferred with a high accuracy (0.76, 0.72, and 0.81, respectively) by relying on an automatic QoL assessment system. Let us note that SLEEPING was the method with the lowest performance. This is due to the fact that, currently in our use case, the system uses only motion sensors. Higher performances could be expected when combining motion sensors with other ones, such as mat-pressure or light sensors. MOBILITY achieved higher performance results than SLEEPING especially when outdoor and indoor features were merged together. In fact, using only outdoor features was not as reliable as combining with indoor. This can be due to the reliability of the GPS system embedded in the smartphone that made some errors in identifying when the user was really away. Let us also note that this is an important result because disabled people in general spend a lot of time at their homes. Finally, MOOD reported the highest performances. Although at a first instance this could be surprising, this fact might be explained considering the intrinsic correlation between SLEEPING and MOBILITY, as highlighted by the questionnaire compiled daily by the users. It is worth noting that higher performances could be expected considering and data mining as well social networking activities performed by the user.

5.1.5 Telemonitoring severely disabled people

Three different metrics (MOBILITY, SLEEPING, and MOOD) were tested for HU1 over more than one month and a half. For multiple reasons 21 days of data of 45 total days could not be considered for the analysis. With so little data it was too difficult to develop a specific regression method. For this reason we proposed three different strategies in order to end up with QoL prediction methods.

The first strategy consisted of reusing the evaluated methods from the control user. This strategy suggested that it is possible to think in one single method for SLEEPING, another for MOBILITY and another for MOOD each one able to provide predictions for any user. On average this method produced a MSE of 2.57 for HU1 (3.64 for MOBILITY, 1.24 for SLEEPING, and 2.85 for MOOD).

The second strategy consisted of producing one predictive method per user. Thus, we merged data from the control user and the specific user and with this data we attempted to produce the best regression methods. On average this method yielded a MSE of 1.03 for HU1 (0.55 for MOBILITY, 1.48 for SLEEPING, and 1.069 for MOOD).

The last strategy consisted of producing one predictive method per user as well. However, in this case we weighted the merged data from the control user and the specific user. Different weights were used. Some gave much more importance to the end user data and others to the control user. On average this method produced a MSE of 1.33 for HU user (0.56 for MOBILITY, 1.53 for SLEEPING, and 1.91 for MOOD).

Hence, we could conclude that the merging strategies worked much better compared to the strategy of reusing the control user methods to predict other end user measures. In other words, a personalized solution should be given for each user. In fact, a general method able to recognize SLEEPING for every user is unfeasible. The same happens for MOBILITY and MOOD. In fact, it is worth noting that answers given to questionnaires are completely subjective depending on the users' behavior and attitude (e.g., optimistic versus pessimistic), their status (e.g., people with mobility impairment versus able-bodied people), and their perception of life (e.g., young people versus elderly people).

5.2 Impact on healthcare, business and society

In a world that is much more digitally enabled than ever before, people living with physical and cognitive disabilities struggle to exert autonomy and independence in their own home and beyond. The BackHome system together with the services it is offering is making a significant contribution for people in need to enhance their opportunities for physical and social inclusion and effective assistance. In fact, with the provision of practical electrodes, easy to use software, and home support tools, BackHome facilitates independent home use of BCI technology, which can already be considered for the first time as an alternative Assistive Technology.

The findings from BackHome present challenges to pave the way for later future improvements to further bridge the gap between a laboratory based BCI and an AT for home use, as well as to improve understanding of brain research. The results have shown that we have reduced the gap between the initial hardware and software laboratory prototypes intended for research and we have developed a final product composed of a highly modular, scalable and distributed architecture ready to host a multi-featured BCI; light, wireless and ergonomic BCI equipment; a one-click set-up and training interface for non-expert caregivers; a complete set of fine-tuned services to satisfy most end-users' needs; a TMHSS to remotely monitor and assist BCI independent use; and a web portal for remote experts and therapists to assess the use of the system and the habits and quality of life of the individual.

Being promising, the potential socio-economic impact of the exploitation of the system, as well as barriers and facilitators for future deployment and spreading of such technologies, have been analyzed. In the very near future, a niche segment of end-users, severe disabled people which are not capable to use eye-trackers and other available technologies, will soon have BCI as their Assistive Technology of choice. BackHome system is therefore a significant achievement in BCI research, specifically linked to the "replace" and "restore" application scenarios.

In a broader perspective, we are investigating how the solution presented in this thesis may reach a larger audience (not only BCI users) providing a better assistance and support to people in need. Some of the components of the BackHome system have the potentiality to provide services of advanced teleassistance, chronic care management, healthy habits promotion and social participation targeted to the elderly, the chronic patient and the disabled not necessarily using BCI as the end-user interface. This is a nice lesson learnt of how research in a complex use case requiring multidisciplinary knowledge, can pave the path to simpler and easier to market innovation solutions which may hit the market and help return the investment in research and development.

Thanks to the new and inexpensive technologies it is now possible and affordable to get information and realize medical tasks remotely. Telemedecine is now a reality and can be applied to several fields of the health practice to assist patients in self-care and adherence to treatments. Telerehabilitation enables following continuous interventions which may improve health conditions (both physical and cognitive) without the need for the patient to physically move to specialized facilities. Teleassistance improves autonomy, safety and social participation of people with special needs, normally the elderly and the disabled, through home support technologies which postpone the need of consumption of socio-sanitary services and associated costs. All of them need Telemonitoring features, which allow therapists and caregivers to be aware of the status of the patients. We may refer to Tele* to name the group of remote solutions in the field of the eHealth (i.e., Telemedicine, Telerehabilitation, Teleassistance all of them with Telemonitoring features). Summarizing, Tele* allows: to improve the quality of clinical services, by facilitating the access to them, helping to break geographical barriers; to center the assistance in the patient, facilitating the communication between different clinical levels; to extend the therapeutic processes beyond the hospital, like patient's home; to save unnecessary costs and reach a better costs/benefits ratio. The corresponding applications allow direct communication between the patient and the professional staff as a common denominator.

5.2.1 New eHealth solutions for a novel healthcare paradigm

The TMHSS of BackHome is leading the path towards a generation of eHealth solutions targeted to a broader audience of users (elderly users, chronic patients, disabled people not necessarily users of BCI or other alternative ATs) which may become technological enablers of the novel healthcare model founded on 4P medicine. Those solutions are implemented with the objective of being highly reliable, scalable and interoperable and becoming a business player in the market of healthcare technologies.

In Chapter 1 we introduced how novel Integrated Care (IC) models are seeking the promotion of collaboration and continuity among care settings, and a move from institutional, reactive care to a home-based, patient-centred, preventive model. IC models will improve efficiency and quality of assistance to ensure sustainability of healthcare. In order to meet IC's ambitious requirements, it will require new organizational models for the adaptive case management of personalised clinical pathways which connect all the professionals, patients and their carers through integrated ICT solutions for all those actors to collaborate and communicate. A key technological requirement is continuous telemonitoring of patients to automatically assess their status and quality

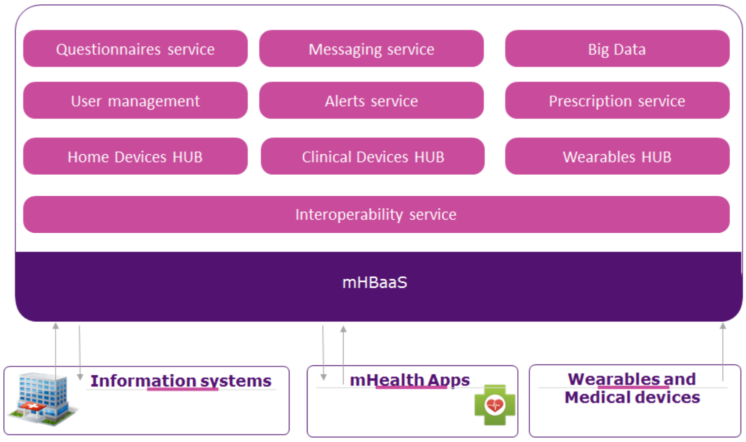

FIGURE 5.1: Usage schema for mHealth Apps to access and make use of generic, added value and interoperability services.

of life enabling recommendations for patients' self-management, besides notifications and alerts for carers and professionals to take more informed decisions in case emergency situations are detected or exacerbations are predicted. The TMHSS of the Back-Home system is leading to a suite of new eHealth solutions, namely, a mobile Health Backend and the associated services eKauri (advanced teleassistance), eKenku (chronic management) and ActivApp (promotion of healthy habits), which we are now presenting here.

mobile Health Backend as a service

All Tele* solutions have the same model and many features in common. In general, all those Tele* solutions follow a closed loop model in which there are at least two stations, the Patient Station and the Therapist Station:

- *The Patient Station* is often at the patient's home or pocket, and it is taking more and more often the shape of a mHealth application or mobile App to be downloaded from a mobile marketplace. One common feature of this station is its ability to get data from the patient, either from sensors (environmental, physiological, biometric) or from the direct interaction with the user through questionnaires, quizzes or games. This trend is leading to non intrusive, wireless sensors, integrated to the station and to the life of the user in a way that produces acceptance instead of rejection. The Patient interacts with the station to check therapy plans, communicate with professionals and get feedback about the progress of therapies.

- *The Therapist Station* is at the clinician or therapist desk, integrated to management tools, and allows the professional to plan, monitor, personalize, evaluate and take decisions regarding the intervention prescribed to the patient and the status and evolution of the patient in charge. This application consists of a dashboard to provide alerts, notifications, automated reports and queries based on the information obtained from patients through telemonitoring features deployed in the patient's side, which supports decisions of professionals in real-time and integrated in their care practice.

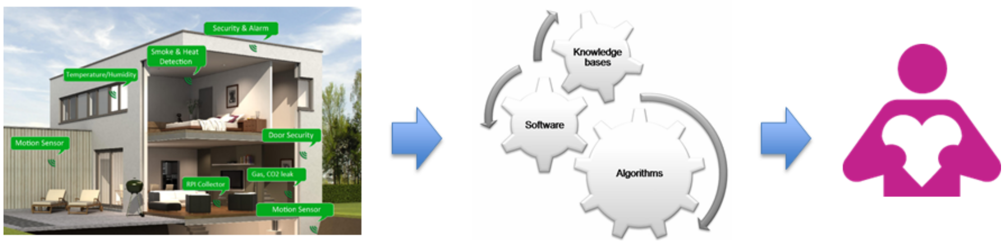

FIGURE 5.2: eKauri uses a home set to get environmental data from elderly people to provide advanced teleassistance services.

The evolution of BackHome's TMHSS has resulted in a "mobile Health Backend as a Service (mHBaaS)", which is a server-side backend which offers generic services (e.g. user management, messaging, alerts, etc.), added value services (e.g. Big Data, data exploitation, etc.) and interoperability services (e.g. standardized interconnection to healthcare providers and administrations), which help to develop and deploy mHealth applications which are aimed to provide Tele* services which are integrated in the care practice and with the current Health Information Systems (HIS). This mHBaaS may be of help to mHealth developers (independent studios, pharma companies, medtech companies, etc.) to boost their development and integration processes. Figure 5.1 illustrates the current services of the mHBaaS for mHealth apps, wearables and devices to use services, send collected data and interoperate with Healthcare Information Systems.

eKauri - An advanced Teleassistance service

eKauri aims to provide advanced teleassistance services to elderly people living alone at home by telemonitoring the environmental data gathered from wireless home automation sensors. A gateway collects and sends the sensor data in real time to the Backend in the cloud, which stores and exploits the data to provide patterns, anomalies and emergency notifications for caregivers, home assistance services and relatives. First-hand information, dashboards and decision support tools provide safety and allow proactive interventions over fragile people, typically elderly people living alone, disabled people or people that need assistance. As pictured in Figure 5.2 the processing of data coming from non intrusive sensors provides query tools, automated reports and alerts tools to predict potential anomalies such as falls, activity decline trends, anomalous behaviors or risk of health problems which may trigger preventive actions to mitigate more complex problems.

eKenku - a chronic management service

eKenku aims to provide home health care services by telemonitoring physiological data from patients at home, complementing it with personalized questionnaires, and setting up videoconferences and other direct contact links between patients and professionals when needed. eKenku ultimately provides self-management tools for chronic patients to become empowered to co-produce their healthcare, and telemonitoring and case management tools for clinicians to manage an integrated and continuous care. As pictured in Figure 5.3 a mobile App wirelessly connected to medical devices enables the collection and processing of data which is used at the clinician's desktop to provide query tools, automated reports and emergency tools to predict exacerbations which may trigger preventive interventions and reduce costly hospital readmissions.

FIGURE 5.3: eKenku uses a mHealth App to get physiologic and personal data from patients in order to provide home health care services.

ActivApp - a service for the promotion of healthy habits

ActivApp aims to provide prescription and remote monitoring of physical activity for the promotion of healthy habits in patients which may improve their condition by working out and becoming physically active. ActivApp is a self-management tool for patients to engage and adhere to a program which may complement very well the pharmacological treatment, because there is very well documented evidence of the benefit of such interventions for improving the condition of patients with heart failure, diabetes, or COPD, among other chronic conditions. ActivApp also includes telemonitoring and case management tools for clinicians to manage and follow-up those non pharmacological interventions with an integrated and continuous care approach. As pictured in Figure 5.4 the capture and processing of data from activity trackers, other sensors and questionnaires operated from a mHealth App provides reports and follow-up tools for therapists to analyze the adherence to treatment and support decisions on intervention fine tuning and activity planning.

Requirements for sustainability and scale-up

There are many issues to be tackled which are common to every Integrated Care (IC) service to be deployed and made sustainable in large-scale and real healthcare scenarios. The most outstanding features and issues to be addressed are briefly outlined here:

- *Privacy and security:* Who has access to the ICT systems? Which authentication methods are used? How identity theft can be prevented? Where is the data stored? Who owns the data? How data privacy and security is guaranteed? Privacy and security is definitely one major issue and barrier for the deployment of Integrated Care solutions. Healthcare data ultimately belongs to the patient, and is one of the most sensitive types of data from the point of view of data protection laws and policies. State of art methods and technologies for user authentication, data storage, data sharing and exchange need to be used, together with highest standards of encryption, secure telecommunication protocols and fault tolerant infrastructures. Those security standards need to be certified by accredited authorities.

- *Interoperability:* How different stakeholders collaborate and exchange information? Do the healthcare providers need to replace their current information systems? How the continuity is ensured between healthcare providers and between the different tiers of one particular provider? This is another key cornerstone of

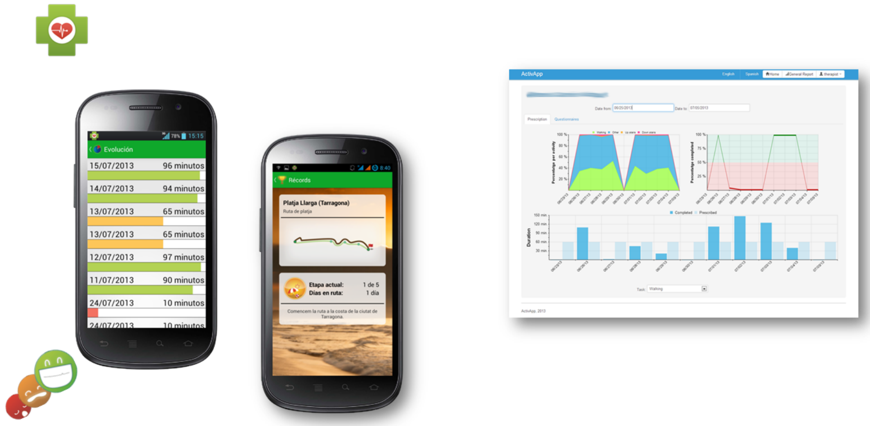

FIGURE 5.4: ActivApp is used to prescribe physical activity and promote adherence through motivation and remote control features.

this business. New Tele* applications and new IC services need to be founded on top of current Hospital Information Systems (HIS), which hold all the information of patients based on Electronic Health Records (EHR), medical images (PACS), workflow management tools and other functionalities. New applications need to neatly integrate with current management applications and information systems for them to be accepted and succeed. In fact, they need to reinforce the initiatives that Healthcare administrations have been advancing over years to promote integration of data and processes, like interoperability frameworks, shared electronic health records (EHR) infrastructures, Personal Health Folders (PHF), and so on. Implementing open applications which make use of internationally accepted standards like HL7 or EN13606 for syntactic interoperability, CT-SNOMED, ICF, ICD-10 for semantic interoperability, Continua Health Alliance for device interoperability, to name only a few, is a must.

- *Adaptive case management:* How healthcare processes can be managed in a collaborative and dynamic way. How to make effective and efficient the planning and follow-up of clinical pathways for patients which evolve over time and bring changing needs? How to act in a preventive, predictive and proactive way? The new healthcare paradigm needs to take a shift from episode management to case management, for patients to be treated continuously and collaboratively during their patient journey. The integration of Tele* tools and IC services into care practice needs management applications which incorporate novel adaptive case management methods and tools, which may facilitate tasks which are complex and unpredictable by nature and require knowledge-work skills.

- *Organizational changes:* Who will implement the new healthcare model? Which new skills are needed? Does the role of professionals (primary care doctors, specialized doctors, nurses, etc.) need to be redefined? Who should lead the governance? Which investments and disinvestments are required? The proposed technology is the enabler, but the main required change for a novel healthcare model is organizational. Specialized hospitals, which are expensive by nature, need to be redefined to empty their currently packed floors, rooms, and emergency rooms of daily routine problems, and focus their activity in the solution of complex uncommon problems, the development of new treatments, and research. Chronic management, for example, needs to be transferred to primary care, which also needs a redefinition with new resources and new skills, to make effective prevention, screening, early diagnosis, home healthcare and virtual continuous follow-up delivered as commodity services. This is a complex change, because requires retraining of professionals, redefinition of roles, empowerment of nurses, and reordering of service provision, to name a few of the required changes.

- *Patient experience:* How is the patient interaction with healthcare systems nowadays? Are patients taken into account for decision making? How can they provide useful inputs which trigger effective change? Which role should patients play? Patient centeredness, the concept of the patient being reallocated to the center of the whole healthcare system, is a common and well accepted message. In fact, patient is the end user, the customer of healthcare system, and all the efforts should end up to keep patient satisfied. Surveys are regularly collected, and some focus groups are conducted to seek their input, but this is not enough. Patient experience must be the engine of innovation in healthcare. New services, new treatments, new pathways, need to be co-created, co-designed together with patients. Patients need to be incorporated into the full life cycle of innovation, since the inception of concepts, to validation and deployment. The novel model of healthcare will only be successful if patient experience is at the core of it.

- *Business models:* Who will pay for new services, specially when they need an investment in technology? Which are the stakeholders who will make services sustainable? Are we only talking about costs, and cost savings, or there is an opportunity for business, incomes and growth? Who will lead this business? The impact of the new Tele* solutions and IC services is first of all clinical, as well as social and technological. The new model seeks efficiencies in the healthcare systems, cost reductions, improvement in quality of assistance and ultimately improvements in the health status of patients and their quality of life. However, all this needs to be founded on business models which make the services and technologies sustainable over time, cost-effective, and even become an opportunity for economical growth, creation of new companies, and job creation. There is an attractive opportunity here, because there is an international demand for these new technologies and services, and there is a big space for growth of this sector. But some barriers need to be overcome. One main factor is payment methods. Public health comes from a long time history of models based on pay-per-service, i.e. pay per visit, pay per admission to the hospital, pay per medical test, pay per day of hospitalization, etc. Models and technologies which seek efficiencies, and actually seek to reduce the number and length of all those traditional services, are clashing against those traditional payment methods. New bundle payments which promote efficiency need to be introduced and improved, and this is only under way. On the other hand, private healthcare and insurances are in general some steps behind the investment in innovation, at least in our closer environment. Healthcare is a domain that is conservative per nature, and digital technologies for transactions which are already common and widespread in banking or retail sectors, are introduced in a slower pace in healthcare, New initiatives like public pre-commercial procurement and public procurement of innovative solutions should impulse the acquisition and adoption of innovative solutions in healthcare environments. The private sector needs to be well prepared: there is a need to have at hand companies which produce top quality technology, which invest in innovation, with capacities to transform R&D outcomes from research groups and technology centers into innovative products and services, and good integration and service provider companies which have the capability to build an offer attractive for healthcare providers, patients and citizens. Healthcare and education should be top priorities of developed countries, therefore it is paramount to align research, innovation, and care management to attain these ambitious and attractive goals.

Chapter 6

Conclusions and future work

6.1 Conclusions

The ambition of this thesis has been to advance in concepts, technology, evidence and impact around the use of ICT to transform healthcare practice towards a new model which promotes radical efficiency and effectiveness, improving quality and ensuring sustainability. The new medicine has been described as 4P: personalized, preventive, predictive and participatory. It requires transformation from analogical to digital, from face to face to virtual, through the deployment of new eHealth solutions. A transformation to improve patient experience.

One key common feature of those novel eHealth solutions is telemonitoring, i.e ICTs to monitor the health status of a patient from a distance which makes possible to remotely assess health status of individuals and ultimately trigger 4P decision making.

Recently, we proposed a methodology to collect, normalize and measure data coming from standardized scales which patients input regularly with the support of caregivers and clinicians. This methodology provided metrics to assess the evolution of the health status of an individual, compare it with others, and even provide decision support in intervention planning. In this thesis we have explored and advanced a broader and more ambitious challenge, Quality of Life (QoL) telemonitoring based on the knowledge of context: for this purpose, we have presented a new generic methodology to telemonitor QoL of individuals with a holistic bio-psycho-social approach.

Our main conclusion is therefore that we have been able to implement and validate this methodology to pervasively assess QoL of individuals in the context of an assistive environment that provides home support to people with severe disabilities. In order to achieve our main goal, we have designed and developed the BackHome system, which aims to improve physical and social autonomy of people with disabilities, for example after having been discharged from a neuro-rehabilitation hospital, through the use of Brain Computer Interfaces (BCIs) .

We have used User Centered Design (UCD) for the first time throughout all development stages of a multi-functional BCI and here lies one of the main innovation drivers of this thesis. Driven by this innovative UCD approach towards independent home use, the BackHome system has achieved five key innovations advancing the current state of the art: (i) a modular and distributed architecture able to meet the requirements of a multi-functional BCI with remote home support; (ii) a novel BCI equipment with practical electrodes aimed at setting a new standard of lightness, autonomy, comfort and reliability; (iii) easy-to use software tailored to people's needs to manage a complete range of multifunctional applications finely tuned for one-click command and adaptive usage; (iv) a telemonitoring and home support system (TMHSS) to remotely monitor and assist BCI independent use; and (v) a Web-based application for therapists which offers remote services to plan and monitor BCI-based cognitive rehabilitation and pervasively assess the QoL of the end-user at home.

This is the first time a multi-functional BCI with such a wide range of services has been evaluated at home by end-users, also taking the therapists' and non-expert caregivers' perspective into account. Results about independent home evaluation of the BackHome system show good acceptance of the system by home users, caregivers and therapists. In fact, results show good acceptance, good usability levels, high user satisfaction and good levels of control, which demonstrate that BCI can be considered for the first time as an alternative Assistive Technology (AT).

Furthermore, we have integrated a TMHSS and a therapy station with a multifunctional BCI system for the first time, opening ways to allow remote communication between therapists and users and improve remote support. We have firstly used the Intelligent Monitoring (IM) engine of our TMHSS to implement and validate activity recognition methods that deal with environments prone to errors. We have introduced a novel and effective hierarchical approach which has improved classification accuracy in detecting if a user is at home, away, alone or with visits, under complex, noisy and unstable environments. Secondly, we have used the BackHome TMHSS to implement and validate a proof of concept of the assessment of QoL based on context data from the user and following the proposed methodology. Results show good accuracies in assessing items of QoL such as Mobility, Sleep, or Mood based on measures and fusion of detected activities from the user. To our best knowledge, this is the first attempt to adopt context-aware techniques to automatically assess QoL.

Eventually, the BackHome system with its integrated TMHSS has been deployed and tested during 6 weeks in real disabled end users' homes for independent home use and for a continuous collection and analysis of data. We have only been able to have a very limited number of end users in the final experiments due to the high cost of equipment, especially BCI, and the uniqueness of the target end user, people with severe disabilities. However, the conclusions were highly satisfactory, both for demonstrating good user acceptance of an heterogeneous and complex technology in a real setting, and for conceptually proving the potential of methodology and technology for remotely assessing activities and QoL of individuals.

6.2 Future Work

In previous chapters, specially in the description of the UCD process of design and development of the BackHome system in Chapter 3, the test and validation outcomes in Chapter 4 and the discussion in previous Chapter 5, we have already been introducing the limitations of the work done and ideas about future lines of progress and improvement.

The multifunctional BCI delivered in the BackHome system, being a very important progress beyond State of Art, presents many opportunities for future work that will need to be researched. Improving the speed of interaction with the BCI, enhancing reliability and robustness of hardware and software, innovating with hybrid BCIs, sliding keywords, fatigue support, and mobile interfaces, fine tuning with personalization features like the dynamic stopping method, improving ergonomics and cost of the equipment, etc. will broaden the use of BCIs to larger audiences beyond those users that cannot use other effective ATs, which are really only a few with really severe disabilities.

The proposed methodology for context aware QoL telemonitoring and the preliminary proof of concept carried out in this work to implement and validate such methodology is still very preliminary and demands extensive future work of analysis, design refinement, development and validation with different use cases and many more scenarios and users. We acknowledge that this is an ambitious approach that is still far from direct application in real care practice.

However, in a broader perspective, and in a shorter term focus, we have also investigated and applied how the solutions presented in this thesis may reach a larger audience (not only BCI users), and cover more feasible features (not necessarily automatic QoL assessment), to help provide a better assistance and support to people in need. Some of the components of the BackHome system (specifically, the TMHSS) have the potentiality to provide services of advanced teleassistance, chronic care management, healthy habits promotion and social participation targeted to the elderly, the chronic patient and the disabled not necessarily using BCI as the end-user interface. In Section 5.2 of last Chapter 5 we have presented how our BackHome TMHSS is leading the path to shorter term solutions like the mHBaaS and the associated services eKauri, eKenku and ActivApp, which will still need future work taking into the account the mentioned requirements for sustainability and scale-up to make the right way into the market and the real care practice. In fact, this is a new market still with changing needs. Anyway, those promising by-products bring a nice lesson learnt of how research in a complex use case requiring multidisciplinary knowledge, can pave the path to simpler and easier to market innovation solutions which may hit the market and help return the investment in research and development.

Appendix A

Publications

This is the list of main publications (referenced in brackets and associated to the corresponding Chapters) which disseminated the research carried out in this thesis:

[148] - Chapters 4 and 5
F. Miralles, E. Vargiu, X. Rafael-Palou, M. Solà, S. Dauwalder, Ch. Guger, Ch. Hintermüller, A. Espinosa, H. Lowish, S. Martin, E. Armstrong, and J. Daly. "Brain Computer Interfaces on Track to Home: Results of the Evaluation at Disabled End-Users's Homes and Lessons Learnt". In: *Frontiers in ICT* 2 (2015), p. 25. DOI: 10.3389/fict.2015.00025.

[52] - Chapter 3
F. Miralles, E. Vargiu, S. Dauwalder, M. Solà, G. Müller-Putz, S.C. Wriessnegger, A. Pinegger, A. Kübler, S. Halder, I. Käthner, S. Martin, J. Daly, E. Armstrong, Ch. Guger, Ch. Hintermüller, and H. Lowish. "Brain Computer Interface on Track to Home". In: *Scientific World Journal* 2015, Article ID 623896 (2015), p. 17. DOI: 10.1155/2015/623896.

[69] - Chapter 1, 3 and 4
F. Miralles, and E. Vargiu. "Providing physical and social autonomy to disabled people through BCI, telemonitoring and home support". In: *Intelligenza Artificiale* 9.1 (2015), pp. 73–87. DOI: 10.3233/IA-150078.

[11] - Chapter 2
F. Miralles, E. Vargiu, E. Casals, J.A. Cordero, and S. Dauwalder. "Automatically Assessing Movement Capabilities through a Sensor-Based Telemonitoring System". In: International Journal of E-Health and Medical Communications (IJEHMC) 6.4 (2015), pp. 39–48. DOI: 10.4018/IJEHMC. 2015100103.

[10] [140] - Chapter 3 and 4
F. Miralles, E. Vargiu, S. Dauwalder, M. Solà, J.M. Fernández, E. Casals, and J.A. Cordero. "Telemonitoring and Home Support in BackHome". In: *Proceedings of the 8th International Workshop on Information Filtering and Retrieval co-located with XIII AI*IA Symposium on Artificial Intelligence (AI*IA 2014)*. Pisa, Italy, 2014.

F. Miralles, E. Vargiu, S. Dauwalder, M. Sola, J.M. Fernández, E. Casals, and J.A. Cordero. "Telemonitoring and Home Support in BackHome". In: Information Filtering and Retrieval (2014), p. 24.
URL: ftp://ceur-ws.org/pub/publications/CEUR-WS/Vol-1314.zip#page=31.

[104] - Chapter 2 and 4
F. Miralles, E. Vargiu, E. Casals, J.A. Cordero, and S. Dauwalder. “Today, how was your ability to move about?” In: Artificial Intelligence and Assistive Medicine (AI-AM/NetMed 2014) (2014), p. 21.
URL: http://ceur-ws.org/Vol-1213/AIAMNETMED2014.pdf#page=28.

[5] - Chapter 1 and 5
F. Miralles, M. Lluch-Ariet, J. Roca, D. Gomez-Cabrero, M. Cascante, J. Tégner, and the Synergy-COPD consortium. “Predictive medicine: outcomes, challenges and opportunities in the Synergy-COPD project”. In: Journal of Translational Medicine (Nov. 2014), 12(Suppl 2):S12. URL:http://www.translational-medicine. com/content/12/S2/S12.

[1] - Chapter 1
F. Miralles. “Health technologies to transform healthcare and industry”. In: Catalunya Economica (Oct. 2013), pp. 12–16. URL: http://www.cateconomica.com/ Articulo / Tecnologias - de - la - salud - para - transformar - la - sanidad.

Next, first page of each of these publications are displayed.

frontiers in ICT

ORIGINAL RESEARCH
published: 25 November 2015
doi: 10.3389/fict.2015.00025

CrossMark

Brain–Computer Interfaces on Track to Home: Results of the Evaluation at Disabled End-Users' Homes and Lessons Learnt

Felip Miralles[1], Eloisa Vargiu[1], Xavier Rafael-Palou[1], Marc Solà[1], Stefan Dauwalder[1], Christoph Guger[2], Christoph Hintermüller[2], Arnau Espinosa[2], Hannah Lowish[3], Suzanne Martin[4], Elaine Armstrong[4] and Jean Daly[4]*

[1] Barcelona Digital Technology Center, Barcelona, Spain, [2] g.tec Medical Engineering GmbH, Schiedlberg, Austria, [3] Telehealth Solutions, Medvivo Group, Wiltshire, UK, [4] The Cedar Foundation, Belfast, UK

The BackHome system is a multifunctional BCI system, the final outcome of a User-Centered Design approach, whose ambition is to move BCI systems from laboratories into the home of people in need for their independent home use. The paper presents the results of testing and evaluation of the BackHome system with end-users at their own homes. Results show moderate to good acceptance from end-users, caregivers, and therapists, which reported promising usability levels, good user satisfaction, and levels of control in the use of services and home support based on remote monitoring tools.

Keywords: brain–computer interface, practical electrodes, user-centered design, telemonitoring and home support, assistive technology, cognitive rehabilitation, teleassistance, end-user evaluation

OPEN ACCESS

Edited by:
Nadia Bianchi-Berthouze,
University College London, UK

Reviewed by:
Fabien Lotte,
National Institute for Research in Computer Science and Control, France
Pascual Gonzalez,
University of Castilla-La Mancha, Spain

****Correspondence:***
Felip Miralles
felip.miralles@eurecat.org

Specialty section:
This article was submitted to Human-Media Interaction, a section of the journal Frontiers in ICT

Received: *03 July 2015*
Accepted: *03 November 2015*
Published: *25 November 2015*

Citation:
Miralles F, Vargiu E, Rafael-Palou X, Solà M, Dauwalder S, Guger C, Hintermüller C, Espinosa A, Lowish H, Martin S, Armstrong E and Daly J (2015) Brain–Computer Interfaces on Track to Home: Results of the Evaluation at Disabled End-Users' Homes and Lessons Learnt. Front. ICT 2:25. doi: 10.3389/fict.2015.00025

1. INTRODUCTION

An important number of research projects in the last number of years have contributed to improve brain–computer interface (BCI) technologies and a number of different applications for this alternative means of human–computer interaction have been produced (Lynch, 2002; Kaufmann et al., 2013). In the roadmap toward 2020 for BCI research proposed by Brunner et al. (2015), applications are targeted at replacing, restoring, or improving the functions of people with some degree of disability as a key objective of future BCI research and innovation. Additionally, BCI use by able-bodied users for enhancing their functions or for broadening their leisure activities is expected to gain momentum and drive research.

The progress of BCI research within those "replace" and "restore" scenarios aim to deliver BCI-based products that represent an alternative to current assistive technologies (AT). Additionally, the progress of BCI research within the "improve" scenario will deliver new rehabilitation methods and tools. The BackHome project[1] has promoted these trends with the ambition to move BCI systems from laboratories and controlled environments into the home of people for their independent use. A number of recent studies have indicated that BCI could be a useful solution for target end-user; however, these studies have also been in controlled environment or laboratory based (Nijboer et al., 2008; Holz et al., 2013; Schreuder et al., 2013; Zickler et al., 2013). User-Centered Design (UCD) has been developed as a way of reducing this gap between the laboratory and the real world use of BCI

[1] www.backhome-fp7.eu/

Hindawi Publishing Corporation
The Scientific World Journal
Volume 2015, Article ID 623896, 17 pages
http://dx.doi.org/10.1155/2015/623896

Research Article

Brain Computer Interface on Track to Home

Felip Miralles,[1] Eloisa Vargiu,[1] Stefan Dauwalder,[1] Marc Solà,[1] Gernot Müller-Putz,[2] Selina C. Wriessnegger,[2] Andreas Pinegger,[2] Andrea Kübler,[3] Sebastian Halder,[3] Ivo Käthner,[3] Suzanne Martin,[4] Jean Daly,[5] Elaine Armstrong,[5] Christoph Guger,[6] Christoph Hintermüller,[6] and Hannah Lowish[7]

[1]*Barcelona Digital Technology Center, C/Roc Boronat 117, 08018 Barcelona, Spain*
[2]*Graz University of Technology, Inffeldgasse 13/4. OG, 8010 Graz, Austria*
[3]*Institute of Psychology, University of Würzburg, Marcusstraße 9-11, 97070 Würzburg, Germany*
[4]*Faculty of life and Health Sciences, University of Ulster, Jordanstown BT370QB, UK*
[5]*Cedar Foundation, 31 Ulsterville Avenue, Belfast BT9 7AS, UK*
[6]*g.tec Guger Technologies OG, Sierningstrasse 14, 4521 Schiedlberg, Austria*
[7]*Telehealth Solutions, Building 6, Suite 7a, Croxley Green Business Park, Hatters Lane, Watford WD18 8YH, UK*

Correspondence should be addressed to Felip Miralles; fmiralles@bdigital.org

Received 7 November 2014; Revised 26 March 2015; Accepted 19 April 2015

Academic Editor: Yusheng Liu

The novel BackHome system offers individuals with disabilities a range of useful services available via brain-computer interfaces (BCIs), to help restore their independence. This is the time such technology is ready to be deployed in the real world, that is, at the target end users' home. This has been achieved by the development of practical electrodes, easy to use software, and delivering telemonitoring and home support capabilities which have been conceived, implemented, and tested within a user-centred design approach. The final BackHome system is the result of a 3-year long process involving extensive user engagement to maximize effectiveness, reliability, robustness, and ease of use of a home based BCI system. The system is comprised of ergonomic and hassle-free BCI equipment; one-click software services for Smart Home control, cognitive stimulation, and web browsing; and remote telemonitoring and home support tools to enable independent home use for nonexpert caregivers and users. BackHome aims to successfully bring BCIs to the home of people with limited mobility to restore their independence and ultimately improve their quality of life.

1. Introduction

Research efforts have improved brain computer interface (BCI) technology in many ways and numerous applications have been prototyped. Motivated by the aim of restoring independence to individuals with severe disabilities, the focus has centred on developing applications [1–3] for communication [4, 5], movement control [6, 7], environmental control [8], locomotion [9], and neurorehabilitation [10–12]. Until recently, these BCI systems have been researched almost exclusively in laboratories. Home usage has been demonstrated, though only with on-going expert supervision. A significant advance on BCI research and its implementation as a feasible assistive technology (AT) is therefore the migration of BCIs into people's homes to provide new options for communication and control that increase independence and reduce social exclusion.

In this context, the EU project BackHome (http://www.backhome-fp7.eu/) is aimed at moving BCIs from being laboratory devices for able-bodies users toward practical devices used at home by people with severe limited mobility. This requires a system that is easy to set up, portable, and intuitive. Thus, BackHome aims to develop BCI systems into practical multimodal ATs to provide useful solutions for communication, web access, leisure, cognitive stimulation, and environmental control and to provide this technology for home usage with minimal support.

The project was designed with a user centred design (UCD) approach at the heart of the whole R&D process in order to move BCIs from the lab towards systems that are

Intelligenza Artificiale 9 (2015) 73–87
DOI 10.3233/IA-150078
IOS Press

Providing physical and social autonomy to disabled people through BCI, telemonitoring and home support

Felip Miralles* and Eloisa Vargiu*
Barcelona Digital Technology Center, Carrer de Roc Boronat 117, Barcelona, Spain

Abstract. Solutions and systems that provide physical and social autonomy to people with severe disabilities must be investigated and designed. In fact, the long term rehabilitation goal for people with disabilites of neurologic origin (caused, for example, by acquired brain injury) is resettlement back in the community away after a discharge. In this paper, we present a solution that relies on BCI, telemonitoring and home support to provide physical and social autonomy to people with acquired brain injury that go back to home after a discharge. We also rely on context-aware techniques to provide a personalized and adaptable solution according to users' needs and preferences. The system is part of the BackHome project and is currently running at end-users facilities in Belfast and Würzburg. Here, we present and discuss experiments performed with healthy users as well as preliminary results with end-users.

Keywords: Physical autonomy, social autonomy, telemonitoring, home support, ambient assisted living, BCI

1. Introduction

Acquired Brain Injury (ABI) as well as other injuries or diseases of neurologic origin limit the individuals capacity for participation and inclusion in society are major causes of disability, and may even cause the so-called "locked-in syndrome"[1]. Assistive technologies are particularly important to enable individual engagement and promote physical and social independence providing benefits to both the people experiencing disability [16, 18] and their carer. In fact, the long term rehabilitation goal for individuals with disabled people of neurologic origin is resettlement back in the community away from institutional care. The ideal scenario is that the person will return to her/his previous home and life roles.

The adoption of a Brain-Computer Interface (BCI) as an assistive technology (AT) extends the potential and contribution that such assistive systems can make through the trajectory of a disability [24, 27]. BCI aims to assist and augment function by developing novel user interfaces, based on the detection of brain signals, ultimately providing communication and control to people with severe disabilities [1, 12, 44].

Telemonitoring and home support provides a wide range of services which enable patients to transition more smoothly into the home environment and be maintained longer and more independent at home [8]. As a technology belonging to integrated care, telemonitoring and home support facilitate services which are convenient for patients, avoiding travel whilst supporting participation in basic healthcare. Moreover, they can become part of a cost effective intervention which promotes personal empowerment [26]. Thus, there are a number of advantages in telemonitoring and home

*Corresponding author: Felip Miralles and Eloisa Vargiu, Barcelona Digital Technology Center, Carrer de Roc Boronat 117, 08018 Barcelona, Spain. Tel.: +34 935534540; E-mail: fmiralles@bdigital.org (Felip Miralles); evargiu@bdigital.org (Eloisa Vargiu).

[1]http://www.cbsnews.com/news/harnessing-the-power-of-the-brain/.

International Journal of E-Health and Medical Communications, 6(4), 39-48, October-December 2015 39

Automatically Assessing Movement Capabilities through a Sensor-Based Telemonitoring System

Felip Miralles, Eurecat, Barcelona, Spain

Eloisa Vargiu, Eurecat, Barcelona, Spain

Eloi Casals, Universitat Pompeu Fabra, Barcelona, Spain

José Alejandro Cordero, Institut de Robòtica i Informàtica Industrial - Universitat Politecnica de Catalunya, Barcelona, Spain

Stefan Dauwalder, Eurecat, Barcelona, Spain

ABSTRACT

Telemonitoring makes possible to remotely assess health status and quality of life of individuals. By acquiring heterogeneous data coming from sensors (physiological, biometric, environmental; non-invasive, adaptive and transparent to user) and data coming from other sources to become aware of user context; by inferring user behaviour and detecting anomalies from this data; and by providing elaborated and smart knowledge to clinicians, therapists, carers, families, and the patients themselves, we will be able to foster preventive, predictive and personalized care actions, decisions and support. In this paper, by relying on a novel sensor-based telemonitoring and home support system, the authors are focused on monitoring mobility activities; the ultimate goal being to automatically assess quality of life of people. In particular, the authors are aimed at answering to an item of a quality-of-life questionnaire, namely "Mobility". Although the authors are interested in assisting disabled people, they performed preliminary experiments with a healthy user, as a proof of concept. Results show that the approach is promising. Thus, the authors are now in the process to install the final system in a number of disabled people's homes under the umbrella of the BackHome project.

Keywords: *Ambient Assisted Living, Assistive Technology, Home Support, Mobility, Quality of Life, Sensor-Based Telemonitoring*

DOI: 10.4018/IJEHMC.2015100103

Telemonitoring and Home Support in BackHome

Felip Miralles, Eloisa Vargiu, Stefan Dauwalder, Marc Solà,
Juan Manuel Fernández, Eloi Casals and José Alejandro Cordero

Barcelona Digital Technology Center,
{fmiralles, evargiu, sdauwalder, msola,
jmfernandez, ecasals, jacordero}@bdigital.org

Abstract. People going back to home after a discharge needs to come back to their normal life. Unfortunately, it becomes very difficult for people with severe disabilities, such as a traumatic brain injury. Thus, this kind of users needs, from the one hand, a telemonitoring system that allows therapists and caregivers to be aware about their status and, from the other hand, home support to be helped in performing their daily activities. In this paper, we present the telemonitoring and home support system developed within the BackHome project. The system relies on sensors to gather all the information coming from user's home. This information is used to keep informed the therapist through a suitable web application, namely Therapist Station, and to automatically assess quality of life as well as to provide context-awareness. Preliminary results in recognizing activities and in assessing quality of life are presented.

1 Introduction

Telemonitoring makes possible to remotely assess health status and Quality of Life (QoL) of individuals. In particular, telemonitoring users' activities allows therapists and caregivers to become aware of user context by acquiring heterogeneous data coming from sensors and other sources. Moreover, Telemonitoring and Home Support Systems (TMHSSs) provide elaborated and smart knowledge to clinicians, therapists, carers, families, and the patients themselves by inferring user behavior. Thus, there are a number of advantages in telemonitoring and home support for both the person living with a disability and the health care provider. In fact, TMHSSs enable the health care provider to get feedback on monitored people and their health status parameters. Hence, a measure of QoL and the level of disability and dependence is provided. TMHSSs provide a wide range of services which enable patients to transition more smoothly into the home environment and be maintained for longer at home [5]. TMHSSs, as an integrated care technology, facilitate services which are convenient for patients, avoiding travel whilst supporting participation in basic healthcare, TMHSS can be a cost effective intervention which promotes personal empowerment [14].
In this paper, we present a sensor-based TMHSS, currently under development in the EU project BackHome[1]. The proposed system is aimed at supporting end users which employ Brain Computer Interface (BCI) as an Assistive Technology (AT) and relies on intelligent techniques to provide both physical and social support in order to improve QoL of people with disabilities. In particular, we are

[1] http://www.backhome-fp7.eu/backhome/index.php

Today, how was your ability to move about?

Felip Miralles, Eloisa Vargiu, Eloi Casals,
José Alejandro Cordero, and Stefan Dauwalder

Barcelona Digital Technology Center,
{fmiralles, evargiu, ecasals, jacordero,
sdauwalder}@bdigital.org

Abstract. In this paper, we are interested in monitoring mobility activities in order to automatically assess quality of life of people. In particular, we are aimed at answering to the question "*Today, how was your ability to move about?*". To this end, we rely on a sensor-based telemonitoring and home support system. Although we are interested in assisting disabled people, we performed preliminary experiments with a healthy user, as a proof of concept. Results show that the approach is promising. Thus, we are now in the process to install the system in disabled people's homes under the umbrella of the BackHome project.

1 Introduction

Improving people's Quality of Life (QoL) is one of the expected outcomes of modern health applications and systems. Thus, several solutions, aimed at improving QoL of the corresponding users, have been investigated and proposed [2]. Among the huge kinds of proposed solutions, let us focus here on those that provide telemonitoring and home support [1], [3], [5]. TeleMonitoring and Home Support Systems (TMHSSs) help users (e.g., disabled or elderly people) to live normally at home keeping (or returning to) their life roles. On the other end, they support health care providers in the task of being aware of the status of their patients.
To assess users' QoL, in the literature several questionnaires have been proposed and adopted [6], [10], [4], [15], [8]. Users are asked to answer to a predefined set of questions about their mental and psychological status and feeling. Although they are largely adopted, as noted in [11], answering them could become tedious and annoying for users and could even be impossible in cases of severe impairment of the user.
In [13] we proposed a generic methodology aimed at automatic assessing QoL of users. Starting from that methodology, among all the items that may compose a QoL questionnaire, in this paper we focus on how to assess the ability to move about. In fact, we use information gathered from a sensor-based TMHSS to answer to the question "*Today, how was your ability to move about?*". Although several works study how to recognize activities [9] and behavior [7], to our best knowledge, this is the first attempt to use that information to automatically assess a (part of a) QoL questionnaire.

2 Materials and Methods

In [13] we proposed a generic methodology to assess and telemonitor QoL of individuals with a holistic bio-psycho-social approach, which intends to become

Miralles *et al. Journal of Translational Medicine* 2014, **12**(Suppl 2):S12
http://www.translational-medicine.com/content/12/S2/S12

JOURNAL OF TRANSLATIONAL MEDICINE

REVIEW Open Access

Predictive medicine: outcomes, challenges and opportunities in the Synergy-COPD project

Felip Miralles[1*], David Gomez-Cabrero[2], Magí Lluch-Ariet[1,6], Jesper Tegnér[2], Marta Cascante[3,4,5], Josep Roca[3,5], Synergy-COPD consortium

Abstract

Background: Chronic Obstructive Pulmonary Disease (COPD) is a major challenge for healthcare. Heterogeneities in clinical manifestations and in disease progression are relevant traits in COPD with impact on patient management and prognosis. It is hypothesized that COPD heterogeneity results from the interplay of mechanisms governing three conceptually different phenomena: 1) pulmonary disease, 2) systemic effects of COPD and 3) co-morbidity clustering.

Objectives: To assess the potential of systems medicine to better understand non-pulmonary determinants of COPD heterogeneity. To transfer acquired knowledge to healthcare enhancing subject-specific health risk assessment and stratification to improve management of chronic patients.

Method: Underlying mechanisms of skeletal muscle dysfunction and of co-morbidity clustering in COPD patients were explored with strategies combining deterministic modelling and network medicine analyses using the Biobridge dataset. An independent data driven analysis of co-morbidity clustering examining associated genes and pathways was done (ICD9-CM data from Medicare, 13 million people). A targeted network analysis using the two studies: skeletal muscle dysfunction and co-morbidity clustering explored shared pathways between them.

Results: (1) Evidence of abnormal regulation of pivotal skeletal muscle biological pathways and increased risk for co-morbidity clustering was observed in COPD; (2) shared abnormal pathway regulation between skeletal muscle dysfunction and co-morbidity clustering; and, (3) technological achievements of the projects were: (i) COPD Knowledge Base; (ii) novel modelling approaches; (iii) Simulation Environment; and, (iv) three layers of Clinical Decision Support Systems.

Conclusions: The project demonstrated the high potential of a systems medicine approach to address COPD heterogeneity. Limiting factors for the project development were identified. They were relevant to shape strategies fostering 4P Medicine for chronic patients. The concept of Digital Health Framework and the proposed roadmap for its deployment constituted relevant project outcomes.

Introduction

Synergy-COPD (2011-14) [1] was an European Union project, within a call dedicated to the Virtual Physiological Human 7th Framework Program, conceived to explore the potential of systems medicine to generate knowledge on underlying mechanisms of chronic obstructive pulmonary disease (COPD) heterogeneities observed in the patients both in terms of clinical manifestations and disease progression [2,3]. A core component of the project was to transfer of the acquired knowledge into the clinical arena with a twofold purpose. Firstly, analysis of the role of a systems approach to COPD heterogeneity to enhance individual health risk assessment and stratification leading to innovative patient management strategies. The second purpose was to identify novel modalities for the interplay between healthcare and biomedical research aiming at fostering deployment of 4P Medicine for patients with chronic disorders [4-6]. Ultimately, Synergy-COPD was designed to generate outcomes in three different dimensions: (i) biomedical area; (ii) information and communication technologies (ICT); and, (iii) transfer into healthcare.

* Correspondence: fmiralles@bdigital.org
[1]Barcelona Digital Technology Centre, Barcelona, Spain
Full list of author information is available at the end of the article

TENDENCIAS

Tecnologías de la salud para transformar la sanidad y la industria

LA TRANSFORMACIÓN DE LA MEDICINA GRACIAS A LAS TIC ES UNA OPORTUNIDAD PARA LA INDUSTRIA, PERO TAMBIÉN, A LARGO PLAZO, PARA CONSEGUIR UN SISTEMA DE SALUD SOSTENIBLE.

Por **FELIP MIRALLES**
Jefe de I+D Salud en Barcelona Digital Centro Tecnológico

Se cumplen unos 15 años del nacimiento del término eHealth y la disciplina asociada en la convergencia de biología e ingeniería, pero es ahora cuando entramos de lleno en la transformación radical de la medicina y la práctica asistencial capacitada por las Tecnologías de la Información y Comunicación (TIC). Lo anunciaba *The Economist* en el cambio de década con el suplemento monográfico *Medicine goes digital*, al tiempo que en la era de teléfonos inteligentes, tabletas y App Stores se introducía y se popularizaba el término derivado mHealth, que añade nuevas posibilidades a la personalización y la ubicuidad de la salud.

¿POR QUÉ HA LLEGADO EL MOMENTO?

Partimos de una importante inversión tecnológica ya realizada en la digitalización de datos, imágenes y procesos. Administraciones, hospitales, centros de atención primaria, oficinas de farmacia y centros sociosanitarios consultan y actualizan el historial electrónico del paciente, sus imágenes y vídeos radiológicos y no radiológicos (endoscopias,

Appendix B

Videos

Those next two videos (referenced with the url to display the video online) illustrate the BackHome system. The first video shows objectives, scenario, target users and features of the BackHome system and its usage. The second video was recorded during real independent home use, and showcases the use of the system in real environments. End-users, caregivers and therapists talk about their experience in the validation process.

See the online videos at:

1. https://www.youtube.com/watch?v=8LCKlwqnnEA
2. https://www.youtube.com/watch?v=yojVeyq6z0Q

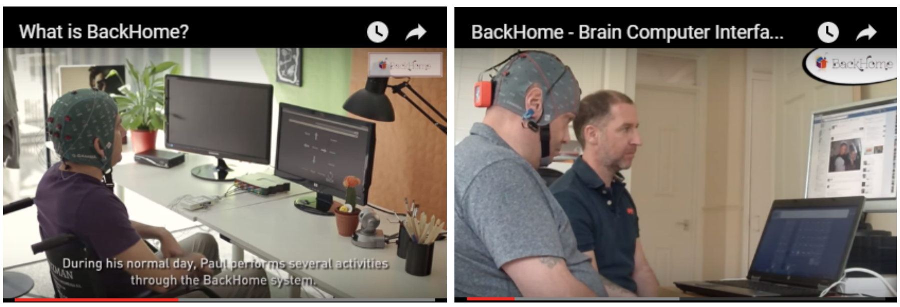

FIGURE B.1: The two online videos which showcase the features of the BackHome system and the validation process

Bibliography

[1] F. Miralles. "Health technologies to transform healthcare and industry". In: *Catalunya Economica* (Oct. 2013), pp. 12–16. URL: http://www.cateconomica.com/Articulo/Tecnologias-de-la-salud-para-transformar-la-sanidad.

[2] "Medicine goes digital". In: *The Economist* (Apr. 2009), Special report. URL: http://www.economist.com/node/13437990.

[3] S. Doménech, J. Rivero, L. Coll-Planas, F.J. Sainz, A. Reissner, and F. Miralles. "Involving Older People in the Design of an Innovative Information and Communication Technologies System Promoting Active Aging: the Saapho Project". In: *Journal of Accessibility and Design for All* 3.1 (2013), p. 15.

[4] D. Gomez-Cabrero, J. Roca, M. Cascante, J. Tégner, M. Lluch-Ariet, F.Miralles, and the Synergy-COPD consortium. "Synergy-COPD: a systems approach for understanding and managing chronic diseases". In: *Journal of Translational Medicine* (Nov. 2014), 12(Suppl 2):S2. URL: http://www.translational-medicine.com/content/12/S2/S2.

[5] F. Miralles, M. Lluch-Ariet, J. Roca, D. Gomez-Cabrero, M. Cascante, J. Tégner, and the Synergy-COPD consortium. "Predictive medicine: outcomes, challenges and opportunities in the Synergy-COPD project". In: *Journal of Translational Medicine* (Nov. 2014), 12(Suppl 2):S12. URL: http://www.translational-medicine.com/content/12/S2/S12.

[6] L. Subirats, L.Ceccaroni, R. Lopez-Blazquez, F. Miralles, A. García-Rudolph, and J.M. Tormos. "Circles of Health: towards an advanced social network about disabilities of neurological origin". In: *Journal of Biomedical Informatics* (Dec. 2013), 46(6),1006–1029.

[7] F. Miralles, L. Ceccaroni, L. Subirats, J.M. Tormos, A. Gil, R. Lopez, and A. Garcia. *SYSTEM AND METHOD FOR EXTRACTING AND MONITORING MULTIDIMENSIONAL ATTRIBUTES REGARDING PERSONAL HEALTH STATUS AND EVOLUTION*. Patent: http://patentscope.wipo.int/search/en/WO2013097905.

[8] M. Calvo, L. Subirats, L. Ceccaroni, J.M. Maroto, C. de Pablo, and F. Miralles. "Automatic assessment of socioeconomic impact in cardiac rehabilitation". In: *Int. J. Environ. Res. Public Health* (2013), 10(11), 5266–5283.

[9] L. Subirats, L. Ceccaroni, and F. Miralles. "Knowledge representation for prognosis of health status in rehabilitation". In: *Future Internet* 4.3 (2012), pp. 762–775.

[10] F. Miralles, E. Vargiu, S. Dauwalder, M. Solà, J.M. Fernández, E. Casals, and J.A. Cordero. "Telemonitoring and Home Support in BackHome". In: *Proceedings of the 8th International Workshop on Information Filtering and Retrieval co-located with XIII AI*IA Symposium on Artificial Intelligence (AI*IA 2014).* Pisa, Italy, 2014.

[11] F. Miralles, E. Vargiu, E. Casals, J.A. Cordero, and S. Dauwalder. “Automatically Assessing Movement Capabilities through a Sensor-Based Telemonitoring System”. In: *International Journal of E-Health and Medical Communications (IJEHMC)* 6.4 (2015), pp. 39–48. DOI: 10.4018/IJEHMC.2015100103.

[12] E. Vargiu, J.M. Fernández, and F. Miralles. “Context-Aware based Quality of Life Telemonitoring”. In: *Distributed Systems and Applications of Information Filtering and Retrieval, Studies in Computational Intelligence. DART 2012: Revised and Invited Papers. C. Lai, A. Giuliani and G. Semeraro (eds.)* Ed. by In C. Lai et al. Springer-Verlag Berlin Heidelberg, 2014, pp. 1–23.

[13] M. Ouwens, H. Wollersheim, R. Hermens, M. Hulscher, and R. Richard. “Integrated care programmes for chronically ill patients: a review of systematic reviews”. In: *International journal for quality in health care* 17.2 (2005), pp. 141–146.

[14] WHO. *Global Age-Friendly Cities: A Guide*. Nonserial Publication. World Health Organization, 2007. ISBN: 9789241547307. URL: http://books.google.es/books?id=4uWtQy6rGywC.

[15] H.J. Sutherland and J.E. Till. “Quality of life assessments and levels of decision making: differentiating objectives.” In: *Qual Life Res* 2.4 (1993), pp. 297–303. ISSN: 0962-9343. URL: http://www.biomedsearch.com/nih/Quality-life-assessments-levels-decision/8220364.html.

[16] C.C. Gotay and T.D. Moore. “Assessing quality of life in head and neck cancer”. In: *Qual Life Res.* 1 (1992), pp. 5–17.

[17] L. Lerer. “The healthcare 2020 platform: The e-health consumer”. PhD thesis. INSEAD, 2000.

[18] B. Schilit, N. Adams, and R. Want. “Context-aware computing applications”. In: *Mobile Computing Systems and Applications, 1994. WMCSA 1994. First Workshop on*. IEEE. 1994, pp. 85–90.

[19] A.K. Dey. “Understanding and Using Context”. In: *Personal Ubiquitous Comput.* 5.1 (Jan. 2001), pp. 4–7. ISSN: 1617-4909.

[20] A. Zimmermann, A. Lorenz, and R. Oppermann. “An operational definition of context”. In: *Modeling and using context*. Springer, 2007, pp. 558–571.

[21] M.J. Field et al. *Telemedicine:A Guide to Assessing Telecommunications for Health Care*. National Academies Press, 1996.

[22] S. Meystre. “The current state of telemonitoring: a comment on the literature”. In: *Telemed J E Health* 11.1 (2005), pp. 63–69.

[23] I. Martín-Lesende, E. Orruño, C. Cairo, A. Bilbao, J. Asua, M. Romo, I. Vergara, J.C. Bayón, R. Abad, E. Reviriego, and J. Larrañaga. “Assessment of a primary care-based telemonitoring intervention for home care patients with heart failure and chronic lung disease. The TELBIL study”. In: *BMC Health Services Research* 11.56 (2011).

[24] S.Barro, D.Castro, M.Fernández-Delgado, S.Fraga, M.Lama, J.M.Rodríguez, and J.A.Vila. “Intelligent Telemonitoring of Critical-Care Patients”. In: *IEEE ENGINEERING IN MEDICINE AND BIOLOGY MAGAZINE* 18 (1999), pp. 80–88.

[25] J.N. Mak and J.R. Wolpaw. “Clinical applications of brain-computer interfaces: current state and future prospects”. In: *Biomedical Engineering, IEEE Reviews in* 2 (2009), pp. 187–199.

[26] N. Birbaumer. “Breaking the silence: brain–computer interfaces (BCI) for communication and motor control”. In: *Psychophysiology* 43.6 (2006), pp. 517–532.

[27] J.R. Wolpaw, N. Birbaumer, D. J. McFarland, G. Pfurtscheller, and T.M. Vaughan. “Brain–computer interfaces for communication and control”. In: *Clinical neurophysiology* 113.6 (2002), pp. 767–791.

[28] A. Kübler, N. Neumann, J. Kaiser, B. Kotchoubey, T. Hinterberger, and N. Birbaumer. “Brain-computer communication: self-regulation of slow cortical potentials for verbal communication”. In: *Archives of physical medicine and rehabilitation* 82.11 (2001), pp. 1533–1539.

[29] J.R. Wolpaw and D.J. McFarland. “Control of a two-dimensional movement signal by a noninvasive brain-computer interface in humans”. In: *Proceedings of the National Academy of Sciences of the United States of America* 101.51 (2004), pp. 17849–17854.

[30] D.J. McFarland, W.A. Sarnacki, and J.R. Wolpaw. “Electroencephalographic (EEG) control of three-dimensional movement”. In: *Journal of Neural Engineering* 7.3 (2010), p. 036007.

[31] F. Cincotti, D. Mattia, F. Aloise, S. Bufalari, G. Schalk, G. Oriolo, A. Cherubini, M.G. Marciani, and F. Babiloni. “Non-invasive brain–computer interface system: towards its application as assistive technology”. In: *Brain research bulletin* 75.6 (2008), pp. 796–803.

[32] J.J. Daly and J.R. Wolpaw. “Brain–computer interfaces in neurological rehabilitation”. In: *The Lancet Neurology* 7.11 (2008), pp. 1032–1043.

[33] B. Otal, E. Vargiu, and F. Miralles. “Towards BCI Cognitive Stimulation: From Bottlenecks to Opportunities”. In: *G. R. Müller-Putz, G. Bauernfeind, C. Brunner, D. Steyrl, S. Wriessnegger, R. Scherer (Eds.), Proceedings of the 6th International Brain-Computer Interface Conference*. Graz, Austria, 2014.

[34] A. Ramos-Murguialday, D. Broetz, M. Rea, L. Läer, Ö. Yilmaz, F.L. Brasil, G. Liberati, M.R. Curado, E. Garcia-Cossio, A. Vyziotis, et al. “Brain–machine interface in chronic stroke rehabilitation: A controlled study”. In: *Annals of neurology* 74.1 (2013), pp. 100–108.

[35] S.G. Mason, A. Bashashati, M. Fatourechi, K.F. Navarro, and G.E. Birch. “A Comprehensive Survey of Brain Interface Technology Designs”. In: *Annals of Biomedical Engineering* 35 (2007), pp. 137–169.

[36] C. Neuper and G. Pfurtscheller. “Neurofeedback Training for BCI Control Brain-Computer Interfaces”. In: ed. by B. Bernhard, G. Pfurtscheller, and B. Allison. The Frontiers Collection. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010. Chap. 4, pp. 65–78.

[37] G. Pfurtscheller, B.Z. Allison, C. Brunner, G. Bauernfeind, T. Solis-Escalante, R. Scherer, T.O. Zander, G. Mueller-Putz, C. Neuper, and N. Birbaumer. “The hybrid BCI.” In: *Frontiers in neuroscience* 4 (2010).

[38] N. Birbaumer, N. Ghanayim, T. Hinterberger, I. Iversen, B. Kotchoubey, A. Kubler, J. Perelmouter, E. Taub, and H. Flor. “A spelling device for the paralysed”. In: *Nature* 398.6725 (1999), pp. 297–298.

[39] G. Pfurtscheller, G.R. Müller-Putz, R. Scherer, and C. Neuper. “Rehabilitation with Brain-Computer Interface Systems”. In: *IEEE Computer* 41.10 (2008), pp. 58–65.

[40] G.R. Müller-Putz and G. Pfurtscheller. "Control of an Electrical Prosthesis With an SSVEP-Based BCI". In: *IEEE Trans. Biomed. Engineering* 55.1 (2008), pp. 361–364.

[41] A. Navarro, L. Ceccaroni, Velickovski F., S. Torrellas, F. Miralles, B. Allison, R. Scherer, and J. Faller. "Context-Awareness as an Enhancement of Brain-Computer Interfaces". In: *III International Workshop on Ambient Assisted Living IWAAL 2011*. 2011.

[42] J. Daly, E. Armstrong, F. Miralles, E. Vargiu, G.R. Müller-Putz, C. Hintermüller, C. Guger, A. Kuebler, and S. Martin. "BackHome: Brain-Neural-Computer Interfaces on Track to Home". In: *RAatE 2012 - Recent Advances in Assistive Technology & Engineering*. 2012.

[43] A. Kübler, E.M. Holz, A. Riccio, C. Zickler, T. Kaufmann, S.C. Kleih, P. Staiger-Sälzer, L. Desideri, E. Hoogerwerf, and D. Mattia. "The User-Centered Design as novel perspective for evaluating the usability of BCI-controlled applications". In: *PloS one* 9.12 (2014), e112392.

[44] E.M. Holz, J. Höhne, P. Staiger-Sälzer, M. Tangermann, and A. Kübler. "Brain–computer interface controlled gaming: Evaluation of usability by severely motor restricted end-users". In: *Artificial intelligence in medicine* 59.2 (2013), pp. 111–120.

[45] C. Zickler, S. Halder, S.C. Kleih, C. Herbert, and A. Kübler. "Brain Painting: Usability testing according to the user-centered design in end users with severe motor paralysis". In: *Artificial intelligence in medicine* 59.2 (2013), pp. 99–110.

[46] M. Schreuder, A. Riccio, M. Risetti, S. Dähne, A. Ramsay, J. Williamson, D. Mattia, and M. Tangermann. "User-centered design in brain–computer interfaces?A case study". In: *Artificial intelligence in medicine* 59.2 (2013), pp. 71–80.

[47] F. Nijboer, E.W. Sellers, J. Mellinger, M.A. Jordan, T. Matuz, A. Furdea, S. Halder, U. Mochty, D.J. Krusienski, T.M. Vaughan, et al. "A P300-based brain–computer interface for people with amyotrophic lateral sclerosis". In: *Clinical neurophysiology* 119.8 (2008), pp. 1909–1916.

[48] E.W. Sellers, T.M. Vaughan, and J.R. Wolpaw. "A brain-computer interface for long-term independent home use". In: *Amyotrophic lateral sclerosis* 11.5 (2010), pp. 449–455.

[49] E.M. Holz, L. Botrel, T. Kaufmann, and A. Kübler. "Long-term independent brain-computer interface home use improves quality of life of a patient in the locked-in state: a case study". In: *Archives of physical medicine and rehabilitation* 96.3 (2015), S16–S26.

[50] T.M. Vaughan, D.J. McFarland, G. Schalk, W. Sarnacki, D.J. Krusienski, E.W. Sellers, J.R. Wolpaw, et al. "The wadsworth BCI research and development program: at home with BCI". In: *Neural Systems and Rehabilitation Engineering, IEEE Transactions on* 14.2 (2006), pp. 229–233.

[51] A. Kübler, G. Müller-Putz, and D. Mattia. "User-centred design in brain-computer interface research and development". In: *Annals of physical and rehabilitation medicine* (2015).

[52] F. Miralles, E. Vargiu, S. Dauwalder, M. Solà, G. Müller-Putz, S.C. Wriessnegger, A. Pinegger, A. Kübler, S. Halder, I. Käthner, S. Martin, J. Daly, E. Armstrong, C. Guger, C. Hintermüller, and H. Lowish. "Brain Computer Interface on Track to Home". In: *The Scientific World Journal* 2015, Article ID 623896 (2015), p. 17. DOI: 10.1155/2015/623896.

[53] A.M. Yohannes, R.C. Baldwin, and M. Connolly. "Mortality predictors in disabling chronic obstructive pulmonary disease in old age". In: *Age and ageing* 31.2 (2002), pp. 137–140.

[54] F. Pitta, T. Troosters, M.A. Spruit, M. Decramer, and R. Gosselink. "Activity monitoring for assessment of physical activities in daily life in patients with chronic obstructive pulmonary disease". In: *Archives of physical medicine and rehabilitation* 86.10 (2005), pp. 1979–1985.

[55] G.A. Meijer, K.R. Westerterp, F.M. Verhoeven, H.B. Koper, and F. ten Hoor. "Methods to assess physical activity with special reference to motion sensors and accelerometers". In: *Biomedical Engineering, IEEE Transactions on* 38.3 (1991), pp. 221–229.

[56] S. Warren. "Wearable and Wireless: Distributed, Sensor-Based Telemonitoring Systems for State of Health". In: *Canadian Journal of Animal Science* 80 (2000), pp. 381–392.

[57] M. Chan, C. Hariton, P. Ringeard, and E. Campo. "Smart house automation system for the elderly and the disabled". In: *Systems, Man and Cybernetics, 1995. Intelligent Systems for the 21st Century., IEEE International Conference on*. Vol. 2. Oct. 1995, pp. 1586–1589.

[58] B.G. Celler, E. D. Ilsar, and W. Earnshaw. "Preliminary results of a pilot project on remote monitoring of functional health status in the home". In: *Engineering in Medicine and Biology Society, 1996. Bridging Disciplines for Biomedicine. Proceedings of the 18th Annual International Conference of the IEEE*. Vol. 1. Oct. 1996, pp. 63–64.

[59] T. Barger, D. Brown, and M. Alwan. "Health status monitoring through analysis of behavioral patterns". In: *8th congress of the Italian Association for Artificial Intelligence (AI*IA) on Ambient Intelligence*. Springer-Verlag, 2003, pp. 22–27.

[60] J. Farringdon and S. Nashold. "Continuous Body Monitoring". In: *Ambient Intelligence for Scientific Discovery*. Ed. by Yang Cai. Vol. 3345. Lecture Notes in Computer Science. Springer Berlin Heidelberg, 2005, pp. 202–223.

[61] D.J. Cook, G.M. Youngblood, and G. Jain. "Algorithms for smart spaces". In: *Technology for Aging, Disability and Independence: Computer and Engineering for Design and Applications, Wiley* (2008).

[62] T.S. Barger, D.E. Brown, and M. Alwan. "Health-status monitoring through analysis of behavioral patterns". In: *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on* 35.1 (2005), pp. 22–27.

[63] F. Zhou, J. Jiao, S. Chen, and D. Zhang. "A Case-Driven Ambient Intelligence System for Elderly in-Home Assistance Applications". In: *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on* 41.2 (Mar. 2011), pp. 179–189.

[64] C.D. Nugent, X. Hong, J. Hallberg, D. Finlay, and K. Synnes. "Assessing the impact of individual sensor reliability within smart living environments". In: *Automation Science and Engineering, 2008. CASE 2008. IEEE International Conference on*. IEEE. 2008, pp. 685–690.

[65] D.J. Cook and S.K. Das. "How smart are our environments? An updated look at the state of the art". In: *Pervasive and mobile computing* 3.2 (2007), pp. 53–73.

[66] E.M. Tapia, S.S. Intille, and K. Larson. *Activity recognition in the home using simple and ubiquitous sensors*. Springer, 2004.

[67] A. Ranganathan, J. Al-Muhtadi, and R.H. Campbell. "Reasoning about uncertain contexts in pervasive computing environments". In: *IEEE Pervasive Computing* 3.2 (2004), pp. 62–70.

[68] R. Jafari, A. Encarnacao, A. Zahoory, F. Dabiri, H. Noshadi, and M. Sarrafzadeh. "Wireless sensor networks for health monitoring". In: *Mobile and Ubiquitous Systems: Networking and Services, 2005. MobiQuitous 2005. The Second Annual International Conference on*. IEEE. 2005, pp. 479–481.

[69] F. Miralles and E. Vargiu. "Providing physical and social autonomy to disabled people through BCI, telemonitoring and home support". In: *Intelligenza Artificiale* 9.1 (2015), pp. 73–87. DOI: 10.3233/IA-150078.

[70] X. Rafael-Palou, E. Vargiu, G. Serra, and F. Miralles. "Improving Activity Monitoring through a Hierarchical Approach". In: *The International Conference on Information and Communication Technologies for Ageing Well and e-Health (ICT 4 Ageing Well)*. 2015.

[71] A. Cieza, S. Geyh, S. Chatterji, N. Kostanjsek, B. Üstün, and G Stucki. "ICF linking rules: an update based on lessons learned". In: *Rehabil. Med.* 37 (2005), pp. 212–218.

[72] L. Ceccaroni and L. Subirats. "Interoperable Knowledge representation in Clinical Decision Support Systems for Rehabilitation". In: *International Journal of Applied and Computational Mathematics* 11.2 (2012), pp. 303–316.

[73] L. Subirats, R. Lopez-Blazquez, L. Ceccaroni, M. Gifre, F. Miralles, A. García-Rudolph, and J.M. Tormos. "Monitoring and Prognosis System Based on the ICF for People with Traumatic Brain Injury". In: *International journal of environmental research and public health* 12.8 (2015), pp. 9832–9847.

[74] S. M. Skevington, M. Lotfy, K. A. O'Connell, and WHOQOL Group. "The World Health Organization's WHOQOL-BREF quality of life assessment: psychometric properties and results of the international field trial. A report from the WHOQOL group." In: *Quality of life research : an international journal of quality of life aspects of treatment, care and rehabilitation* 13.2 (Mar. 2004), pp. 299–310. ISSN: 0962-9343. URL: http://view.ncbi.nlm.nih.gov/pubmed/15085902.

[75] D.L. Patrick and P. Erickson. *Health status and health policy: quality of life in health care evaluation and resource allocation*. Health Status and Health Policy: Quality of Life in Health Care Evaluation and Resource Allocation p. 314. Oxford University Press, 1993. ISBN: 9780195050271. URL: http://books.google.es/books?id=IjgQAQAAMAAJ.

[76] M.J. Naughton, S.A. Shumaker, R.T. Anderson, and S.M. Czajkowski. "Psychological Aspects of HealthRelated Quality of Life Measurement: Tests and Scales". In: *Quality of Life and Pharmaco economics in Clinical Trials* 15 (1996), pp. 117–131.

[77] P. Hitzler, M. Krötzsch, B. Parsia, P.F. Patel-Schneider, and S. Rudolph, eds. *OWL 2 Web Ontology Language: Primer*. W3C Recommendation, 2009.

[78] B. Murphy, H. Herrman, G. Hawthorne, T. Pinzone, and H. Evert. *Australian WHOQoL instruments: User's manual and interpretation guide*. Australian WHOQoL Field Study Centre. Melbourne, Australia, 2000.

[79] The Euroqol Group. "Euroqol a facility for the measurement of health-related quality of life". In: *Health Policy* 16 (1990), pp. 199–208.

[80] R.D. Hays, L.S. Morales, Program RAND Health, and Corporation RAND. *The RAND-36 Measure of Health-related Quality of Life*. RAND Health reprint. RAND, 2001.

[81] J.E. Ware, M. Kosinski, and J.E. Dewey. *How to Score Version 2 of the SF-36 Health Survey: Standars & Acute Forms*. QualityMetric, 2001.

[82] Corporation RAND, Program Health Sciences, R.D. Hays, C.D. Sherbourne, and R.M. Mazel. *RAND 36-item Health Survey 1.0: RAND Health Sciences Program*. RAND reprints. RAND, 1992. URL: http://books.google.es/books?id=FUkKHAAACAAJ.

[83] S.B. O'Sullivan and T.J. Schmitz. *Physical Rehabilitation*. G - Reference, Information and Interdisciplinary Subjects Series. F.A. Davis, 2007. ISBN: 9780803612471.

[84] T. Gross and M. Specht. "Awareness in context-aware information systems". In: *Mensch & Computer 2001*. Springer, 2001, pp. 173–182.

[85] S. Bhattacharyya, R.A. Saravanagru, and A. Thangavelu. "Context aware healthcare application". In: *IJCA-International Journal of Computer Applications* 22.3 (2011).

[86] H.E. Byun and K. Cheverst. "Exploiting user models and context-awareness to support personal daily activities". In: *Workshop in UM2001 on User Modeling for Context-Aware Applications*. Citeseer. 2001.

[87] S.S. Intille, P. Kaushik, and R. Rockinson. "Deploying Context-Aware Health Technology at Home: Human-Centric Challenges". In: *Human-Centric Interfaces for Ambient Intelligence* (2009).

[88] M.E. Cordisco, A. Benjaminovitz, K. Hammond, and D. Mancini. "Use of telemonitoring to decrease the rate of hospitalization in patients with severe congestive heart failure". In: *Am J Cardiol* 84.7 (1999), pp. 860–862.

[89] N.T. Artinian, O.G.M. Washington, and Templin T.N. "Effects of home telemonitoring and community-based monitoring on blood pressure control in urban African Americans: A pilot study". In: *Heart Lung* 30 (2001), pp. 191–199.

[90] J.A. Vincent, D.L. Cavitt, and P.P. Karpawich. "Diagnostic and cost effectiveness of telemonitoring the pediatric pacemaker patient". In: *Pediatr Cardiol.* 18.2 (1997), pp. 86–90.

[91] D. Carneiro, R. Costa, P. Novais, J. Machado, and J. Neves. "Simulating and monitoring ambient assisted living". In: *Proc. ESM*. 2008.

[92] J.M. Corchado, J. Bajo, D.I. Tapia, and A. Abraham. "Using heterogeneous wireless sensor networks in a telemonitoring system for healthcare". In: *IEEE Transactions on Information Technology in Biomedicine* 14.2 (2010), pp. 234–240.

[93] M. Mitchell, C. Meyers, A.I. Wang, and G. Tyson. "ContextProvider: Context awareness for medical monitoring applications". In: *Conf Proc IEEE Eng Med Biol Soc*. 2011.

[94] C. Holzner, S. Schaffelhofer, C. Guger, C. Groenegress, G. Edlinger, and M. Slater. "Using a P300 Brain-Computer Interface for Smart Home Control". In: *World Congress 2009*. Munich, Germany, 2009.

[95] L. Tonin, R. Leeb, M. Tavella, S. Perdikis, and J.d.R. Millán. "A BCI-driven Telepresence Robot". In: *International Journal of Bioelectromagnetism* 13(3) (2011), pp. 125 –126.

[96] G. Edlinger, C. Holzner, and C. Guger. "A hybrid brain-computer interface for smart home control". In: *Proceedings of the 14th international conference on Human-computer interaction: interaction techniques and environments - Volume Part II*. HCII'11. Orlando, FL: Springer-Verlag, 2011, pp. 417–425.

[97] J. M. Fernández, S. Dauwalder, S. Torrellas, J. Faller, R. Scherer, P. Omedas, P. Verschure, A. Espinosa, C. Guger, C. Carmichael, U. Costa, E. Opisso, J.M. Tormos, and F. Miralles. "Connecting the disabled to their physical and social world: The BrainAble experience". In: *TOBI Workshop IV Practical Brain-Computer Interfaces for End-Users: Progress and Challenges*. 2013.

[98] G.R. Müller, C. Neuper, and G. Pfurtscheller. "Implementation of a telemonitoring system for the control of an EEG-based brain-computer interface". In: *Neural Systems and Rehabilitation Engineering, IEEE Transactions on* 11.1 (2003), pp. 54–59.

[99] E. Vargiu, L. Ceccaroni, L. Subirats, S. Martin, and F. Miralles. "User Profiling of People with Disabilities - A Proposal to Pervasively Assess Quality of Life". In: *5th International Conference on Agents and Artificial Intelligence*. Barcelona, Spain, 2013.

[100] E. Vargiu, F. Miralles, S. Martin, and D. Markey. "BackHome: Assisting and Telemonitoring People with Disabilities". In: *RAatE 2012 - Recent Advances in Assistive Technology & Engineering*. 2012.

[101] E. Vargiu, J.M. Fernández, S. Torrellas, S. Dauwalder, M. Solà, and F. Miralles. "A Sensor-based Telemonitoring and Home Support System to Improve Quality of Life through BNCI". In: *12th European AAATE Conference*. Vilamoura, Portugal, 2013.

[102] S. Geyh, A. Cieza, B. Kollerits, G. Grimby, and G. Stucki. "Content comparison of health-related quality of life measures used in stroke based on the international classification of functioning, disability and health (ICF): a systematic review". In: *Quality of Life Research* 16.5 (June 2007), pp. 833–851.

[103] M. Nambu, K. Nakajima, M. Noshiro, and T. Tamura. "An algorithm for the automatic detection of health conditions". In: *Engineering in Medicine and Biology Magazine, IEEE* 24.4 (2005), pp. 38–42.

[104] F. Miralles, E. Vargiu, E. Casals, J.A. Cordero, and S. Dauwalder. "Today, how was your ability to move about?" In: *Artificial Intelligence and Assistive Medicine (AI-AM/NetMed)* (2014), p. 21. URL: http://ceur-ws.org/Vol-1213/AIAMNETMED2014.pdf#page=28.

[105] C. Brunner, N. Birbaumer, B. Blankertz, C. Guger, A. Kübler, D. Mattia, J. del R. Millán, F. Miralles, A. Nijholt, E. Opisso, et al. "BNCI Horizon 2020: towards a roadmap for the BCI community". In: *Brain-Computer Interfaces* ahead-of-print (2015), pp. 1–10.

[106] C. Brunner, B. Blankertz, F. Cincotti, A. Kübler, D. Mattia, F. Miralles, A. Nijholt, B. Otal, P. Salomon, and G.R. Müller-Putz. "BNCI Horizon 2020–Towards a Roadmap for Brain/Neural Computer Interaction". In: *Universal Access in Human-Computer Interaction. Design and Development Methods for Universal Access*. Springer, 2014, pp. 475–486.

[107] C. Hintermüller, E. Vargiu, S. Halder, J. Daly, F. Miralles, H. Lowish, N. Anderson, S. Martin, and G. Edlinger. "Brain Neural Computer Interface for Everyday Home Usage". In: *Universal Access in Human-Computer Interaction. Access to Interaction*. Springer, 2015, pp. 437–446.

[108] A. Kübler, B. Kotchoubey, T. Hinterberger, N. Ghanayim, J. Perelmouter, M. Schauer, C. Fritsch, E. Taub, and N. Birbaumer. "The thought translation device: a neurophysiological approach to communication in total motor paralysis". In: *Experimental Brain Research* 124.2 (1999), pp. 223–232.

[109] C Neuper, GR Müller, A Kübler, N Birbaumer, and G Pfurtscheller. "Clinical application of an EEG-based brain–computer interface: a case study in a patient with severe motor impairment". In: *Clinical neurophysiology* 114.3 (2003), pp. 399–409.

[110] I. Käthner, J. Daly, S. Halder, J. Räderscheidt, E. Armstrong, S. Dauwalder, C. Hintermüller, A. Espinosa, E. Vargiu, A. Pinegger, J. Faller, S. Wriessnegger, F. Miralles, H. Lowish, D. Markey, G.R. Müller-Putz, S. Martin, and A. Kübler. "A P300 BCI for e-inclusion, cognitive rehabilitation and smart home control". In: *G. R. Müller-Putz, G. Bauernfeind, C. Brunner, D. Steyrl, S. Wriessnegger, R. Scherer (Eds.), Proceedings of the 6th International Brain-Computer Interface Conference*. Graz, Austria, 2014, pp. 60–63.

[111] B. Allison. "The I of BCIs: Next generation interfaces for brain–computer interface systems that adapt to individual users". In: *Human-Computer Interaction. Novel Interaction Methods and Techniques*. Springer, 2009, pp. 558–568.

[112] C. Zickler, A. Riccio, F. Leotta, S. Hillian-Tress, S. Halder, E. Holz, P. Staiger-Sälzer, E. Hoogerwerf, L. Desideri, D. Mattia, et al. "A brain-computer interface as input channel for a standard assistive technology software". In: *Clinical EEG and Neuroscience* 42.4 (2011), pp. 236–244.

[113] E. Thomson, S. Mathews, D. Todd, P.J. McCullagh, M.P. Ware, M.D. Mulvenna, and S. Martin. "Developing brain computer interfaces with rapid automated interfaces for non experts". In: *Gerontechnology* 9.2 (2010), p. 255.

[114] J.E. Huggins, P.A. Wren, and K.L. Gruis. "What would brain-computer interface users want? Opinions and priorities of potential users with amyotrophic lateral sclerosis". In: *Amyotrophic Lateral Sclerosis* 12.5 (2011), pp. 318–324.

[115] P. Fiedler, P. Pedrosa, S. Griebel, C. Fonseca, F. Vaz, E. Supriyanto, F. Zanow, and J. Haueisen. "Novel Multipin Electrode Cap System for Dry Electroencephalography". In: *Brain topography* (2015), pp. 1–10.

[116] C. Grozea, C.D. Voinescu, and S. Fazli. "Bristle-sensors—low-cost flexible passive dry EEG electrodes for neurofeedback and BCI applications". In: *Journal of neural engineering* 8.2 (2011), p. 025008.

[117] C. Grozea and C. Voinescu. "Bristlesensors–Soft, Flexible Dry EEG Electrodes for Neurofeedback and BCI Applications". In: *4th BCI Meeting, Monterey USA*. 2010.

[118] G. Schalk, D.J. McFarland, T. Hinterberger, N. Birbaumer, and J.R. Wolpaw. "BCI2000: a general-purpose brain-computer interface (BCI) system". In: *Biomedical Engineering, IEEE Transactions on* 51.6 (2004), pp. 1034–1043.

[119] ISO 9241-210 ISO. *Ergonomics od Human-System Interaction - Part 210: Human-Centred Design for Interactive Systems*.

[120] J.R. Wolpaw, H. Ramoser, D.J. McFarland, and G. Pfurtscheller. "EEG-based communication: improved accuracy by response verification". In: *Rehabilitation Engineering, IEEE Transactions on* 6.3 (1998), pp. 326–333.

[121] L. Demers, R. Weiss-Lambrou, and B. Ska. "The Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST 2.0): an overview and recent progress". In: *Technology and Disability* 14.3 (2002), pp. 101–105.

[122] G. Edlinger, C. Holzner, and C. Guger. "A hybrid brain-computer interface for smart home control". In: *Human-computer interaction. Interaction techniques and environments*. Springer, 2011, pp. 417–426.

[123] J. Daly, E. Armstrong, E. Thomson, A. Pinneger, S. Martin, et al. "P300 brain computer interface control after an acquired brain injury". In: *International Journal on recent and innovation trends in computing and communication* 3.1 (2015), pp. 318–325.

[124] J. Daly, A. Pinegger, E. Armstrong, E. Thomson, G. Müller-putz, and S. Martin. "In Pursuit of an Easy to Use Brain Computer Interface for Domestic Use in a Population with Brain Injury". In: *International Journal on recent and innovation trends in computing and communication* 3.1 (2015), pp. 318–325.

[125] C. Carmichael and P. Carmichael. "BNCI systems as a potential assistive technology: ethical issues and participatory research in the BrainAble project". In: *Disability and Rehabilitation: Assistive Technology* 9.1 (2014), pp. 41–47.

[126] W. Glannon. "Ethical issues with brain-computer interfaces". In: *Frontiers in systems neuroscience* 8 (2014).

[127] E. Vargiu, S. Dauwalder, J. Daly, E. Armstrong, S. Martin, and F. Miralles. "Cognitive Rehabilitation through BNCI: Serious Games in BackHome". In: *G. R. Müller-Putz, G. Bauernfeind, C. Brunner, D. Steyrl, S. Wriessnegger, R. Scherer (Eds.), Proceedings of the 6th International Brain-Computer Interface Conference*. Graz, Austria, 2014, pp. 36–39.

[128] S. Doménech, J. Rivero, L. Coll-Planas, F.J. Sainz, A. Reissner, and F. Miralles. "Involving Older People in the Design of an Innovative Information and Communication Technologies System Promoting Active Aging: the Saapho Project". In: *Journal of Accessibility and Design for All* 3.1 (2013), p. 15.

[129] L.A. Farwell and E. Donchin. "Talking off the top of your head: toward a mental prosthesis utilizing event-related brain potentials". In: *Electroencephalography and clinical Neurophysiology* 70.6 (1988), pp. 510–523.

[130] J. Polich. "Updating P300: an integrative theory of P3a and P3b". In: *Clinical neurophysiology* 118.10 (2007), pp. 2128–2148.

[131] C. Kapeller, C. Hintermuller, M. Abu-Alqumsan, R. Pruckl, A. Peer, and C. Guger. "A BCI using VEP for continuous control of a mobile robot". In: *Engineering in Medicine and Biology Society (EMBC), 2013 35th Annual International Conference of the IEEE*. IEEE. 2013, pp. 5254–5257.

[132] C. Hintermüller, C. Kapeller, G. Edlinger, and C. Guger. “BCI Integration: Application Interfaces, Brain-Computer Interface Systems - Recent Progress and Future Prospects”. In: *InTech*. 2013.

[133] T. Kaufmann, S.M. Schulz, A. Köblitz, G. Renner, C. Wessig, and A. Kübler. “Face stimuli effectively prevent brain–computer interface inefficiency in patients with neurodegenerative disease”. In: *Clinical Neurophysiology* 124.5 (2013), pp. 893–900.

[134] J. Münssinger, S. Halder, S. Kleih, A. Furdea, V. Raco, A. Hösle, and A. Kübler. “Brain Painting: First Evaluation of a New Brain Computer Interface Application with ALS-Patients and Healthy Volunteers”. In: *Front Neurosci* 4:182. doi: 10.3389/fnins.2010.00182 (2010).

[135] E.M. Holz, L. Botrel, T. Kaufmann, and A. Kübler. “Long-term independent BCI home-use by a locked-in end-user: an evaluation study”. In: *Procedings of the Fifth International Brain Computer Interface Meeting*. 2013.

[136] E.M. Holz, L. Botrel, and A. Kübler. “Independent BCI use in two patients diagnosed with amyotrophic lateral sclerosis”. In: *Proceedings of the 6th International Brain-Computer Interface Conference*. Graz University of Technology, Verlag der Technischen Universität Graz. 2014, pp. 92–5.

[137] E.M. Mugler, C. Ruf, S. Halder, M. Bensch, A. Kübler, et al. “Design and implementation of a P300-based brain-computer interface for controlling an internet browser”. In: *Neural Systems and Rehabilitation Engineering, IEEE Transactions on* 18.6 (2010), pp. 599–609.

[138] S. Halder, A. Pinegger, I. Käthner, S.C. Wriessnegger, J. Faller, J.B. Antunes, G.R. Müller-Putz, and A. Kübler. “Brain-controlled applications using dynamic P300 speller matrices”. In: *Artificial intelligence in medicine* 63.1 (2015), pp. 7–17.

[139] A. Pinegger, L. Deckert, S. Halder, N. Barry, J. Faller, I. Kathner, C. Hintermuller, S.C. Wriessnegger, A. Kubler, and G.R. Muller-Putz. “Write, read and answer emails with a dry ‘n’wireless brain-computer interface system”. In: *Engineering in Medicine and Biology Society (EMBC), 2014 36th Annual International Conference of the IEEE*. IEEE. 2014, pp. 1286–1289.

[140] F. Miralles, E. Vargiu, S. Dauwalder, M. Sola, J.M. Fernández, E. Casals, and J.A. Cordero. “Telemonitoring and Home Support in BackHome”. In: *Information Filtering and Retrieval* (2014), p. 24. URL: ftp://ceur-ws.org/pub/publications/CEUR-WS/Vol-1314.zip#page=31.

[141] X. Rafael-Palou, E. Vargiu, S. Dauwalder, and F. Miralles. “Monitoring and Supporting People that Need Assistance: the BackHome Experience”. In: *DART 2014: Revised and Invited Papers. C. Lai, A. Giuliani and G. Semeraro (eds.)* 2014.

[142] E. Casals, J.A. Cordero, S. Dauwalder, J.M. Fernández, M. Solà, E. Vargiu, and F. Miralles. “Ambient Intelligence by ATML: Rules in BackHome”. In: *Emerging ideas on Information Filtering and Retrieval. DART 2013: Revised and Invited Papers; C. Lai, A. Giuliani and G. Semeraro (eds.)* 2014.

[143] J.M. Fernández, S. Torrellas, S. Dauwalder, M. Solà, E. Vargiu, and F. Miralles. “Ambient-Intelligence Trigger Markup Language: A new approach to Ambient Intelligence rule definition”. In: *13th Conference of the Italian Association for Artificial Intelligence (AI*IA 2013). CEUR Workshop Proceedings, Vol. 1109*. Turin, Italy, 2013.

[144] X. Rafael-Palou, E. Vargiu, and F. Miralles. "Monitoring People that Need Assistance through a Sensor-based System: Evaluation and First Results". In: *Proceedings of AI-AM/NetMed 2015, Artificial Intelligence and Assistive Medicine (AIME 2015), CEUR Workshop Proceedings, Vol. 1389.* Pavia, Italy, 2015.

[145] E. Vargiu, X. Rafael-Palou, and F. Miralles. "Experimenting Quality of Life Telemonitoring in a Real Scenario". In: *Artificial Intelligence Research* 4.2 (2015), pp. 136–142.

[146] M. Markou and S. Singh. "Novelty detection: a review?part 1: statistical approaches". In: *Signal processing* 83.12 (2003), pp. 2481–2497.

[147] J.M. Fernández, M. Solà, A. Steblin, E. Vargiu, and F. Miralles. "The Relevance of Providing Useful Information to Therapists and Caregivers in Tele*". In: *DART 2014: Revised and Invited Papers. C. Lai, A. Giuliani and G. Semeraro (eds.)* 2014.

[148] F. Miralles, E. Vargiu, X. Rafael-Palou, M. Solà, S. Dauwalder, C. Guger, C. Hintermüller, A. Espinosa, H. Lowish, S. Martin, E. Armstrong, and J. Daly. "Brain Computer Interfaces on Track to Home: Results of the Evaluation at Disabled End-Users's Homes and Lessons Learnt". In: *Frontiers in ICT* 2 (2015), p. 25. DOI: 10.3389/fict.2015.00025.

[149] S.G. Hart and L.E. Staveland. "Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research". In: *Advances in psychology* 52 (1988), pp. 139–183.

[150] X. Rafael-Palou, C. Zambrana, E. Vargiu, and F. Miralles. "Home-Based Activity Monitoring of Elderly People Through a Hierarchical Approach". In: *Information and Communication Technologies for Ageing Well and e-Health*. Springer, 2015, pp. 145–161.

[151] M. Datar, A. Gionis, P. Indyk, and R. Motwani. "Maintaining stream statistics over sliding windows". In: *SIAM Journal on Computing* 31.6 (2002), pp. 1794–1813.

[152] B. Schölkopf, J.C. Platt, J. Shawe-Taylor, A.J. Smola, and R.C. Williamson. "Estimating the support of a high-dimensional distribution". In: *Neural computation* 13.7 (2001), pp. 1443–1471.

[153] M. Fernández-Delgado, E. Cernadas, S. Barro, and D. Amorim. "Do we need hundreds of classifiers to solve real world classification problems?" In: *The Journal of Machine Learning Research* 15.1 (2014), pp. 3133–3181.

[154] C.J. van Rijsbergen. "Towards an information logic". In: *ACM SIGIR Forum*. Vol. 23. SI. ACM. 1989, pp. 77–86.