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Aging Neuro-Behavior Ontology

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Abstract. It is known that the aging process entails a cognitive decline in certain processes such as attention, episodic memory, working memory, processing speed and executive functions. In recent years, efforts have been made to investigate the potential of Information and Communication Technologies to improve cognitive functioning and quality of life in older adults with and without cognitive impairments. In this paper, we propose the Aging Neuro-Behaviour Ontology (ANBO), a formal model of cognitive processes involved in day-to-day living and whose performance usually decline with age. ANBO has been created with the aim of being an aid in developing tools for cognitive rehabilitation by means of integrating aging-related behaviors with monitoring activities of daily living. As an example of these tools, we introduce an integration of ANBO with the Ontology SmartLab Elderly (OSLE), an ontology related with Telehealth Smart Homes wherein activities of daily living are recorded. This ANBO and OSLE integration enable the interpretation of these activities as the result of cognitive processes of interest in the domain of elderly decline.

Keywords. elderly, neuro-psychology,, ontology engineering, ambient intelligence

1. Introduction

Cognition is a collection of brain-based functions which allow us to interact successfully with the world around us. These cognitive abilities are necessary to carry out any activity of daily living (ADL), from the simplest to the most complex tasks. Thus, daily tasks can be defined by the degree to which they require specific cognitive operations and it is possible classify functional tasks based on required cognitive abilities (Lawton and Brody, 1970; Farias et al., 2008). For instance, driving is a task that takes place in complex environments and it requires organizing and implementing various sub-tasks such as controlling speed, interpreting abstract signs, planning the best route, and planning alternative routes in the case of unforeseen events. Even the simplest activities, such as answering the telephone, require the programming and use of different cognitive operations: per-

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ception (hearing the ring tone), decision making (answering or not), motor skills (lifting the receiver), language (producing and understanding language), and social skills (interpreting tone of voice and interacting properly with another human being). Some of the main cognitive capacities are:

- **Perception** permits recognition and interpretation of sensory stimuli (smell, touch, hearing,etc) (Bruce and Young, 1986; Humphreys and Riddoch, 2017; Young and Bruce, 2011).
- **Attention** is a complex mechanism with several different facets (focused, sustained, selective, alternating and divided). This capacity is considered a central control mechanism and its principal function is to direct and guide the conscious activity of the organism according to a specific goal or objective (Posner and Dehaene, 1994).
- **Memory**. Learning and human memory are part of a complex processing system (short-term/working memory - limited storage, long-term memory - unlimited storage, implicit and explicit memory) that is in charge of coding, storing, building, reconstructing and recovering perceptions, knowledge, facts, abilities, emotions, plans, etc (Atkinson and Shiffrin, 1968; Baddeley, 1992, 2000; Tulving and Craik, 2000).
- **Language** forms one of the very complex human capacities that allow us to communicate thoughts, ideas, feelings, doubts, desires and needs (García-Viedma and Fernández-Guinea, 2010; Patterson and Shewell, 2013).
- **Executive functions** are abilities that allow us to transform our thoughts into actions efficiently. According to Lezak (1995) these can be grouped into the following components: formulations of goals, planning processes and strategies to achieve objectives (to establish steps or action items, to evaluate different alternatives), monitoring and supervision of action (recognition of achievement or non-achievement, flexibility or capacity for quickly switching to the appropriate mental mode), and efficient performance of the plans (control, correction, self-regulation of time and other qualities of execution).

Each cognitive ability plays an important part in the processing of new information. If one of these processes has deficits, the correct functioning of the other operations will be affected, and these impairments lead to difficulties in carrying out ADLs. Loss of cognitive functions causes interference with social ad occupational functioning. Consequently, functional independence and quality of life may be diminished.

The normal aging process entails changes in cognition. Although some cognitive functions, including world knowledge, verbal abilities and implicit memory are preserved in older adults (Ballesteros et al., 2013; Park et al., 2002; Wiggs et al., 2006), this aging process is associated with an important decrease in certain cognitive functions such as attention, episodic memory, working memory, processing speed, and executive functions (Rönnlund et al., 2005; Salthouse, 2010). These deficits do not have a significant impact on ADLs and functional independence, but these difficulties often progress into more serious conditions such as Mild Cognitive Impairment (MCI) or dementia, principally Alzheimer's disease (AD; Brown et al., 2011; Jekel et al., 2015). Detecting functional decline along the continuum from normal aging to dementia is crucial because these difficulties are considered a risk factor and prodromal stage of the dementia. Assessment of daily living activities would also allow to identify abnormal behaviors as indicators of cognitive decline and it is an important aspect of neuropsychological evaluation. So that some functional instruments have been development to measure deficit and change in domains of everyday functioning relevant to specific cognitive domain, such as ECog (Farias et al., 2008).

The cognitive changes are evident in aging process. However, previous findings show that cognitive training interventions and programs can improve cognition in healthy older adults (Ball et al., 2002). Thus, training cognitive abilities delays cognitive decline and helps older individuals to maintain independence and a higher quality of life for longer.

ANBO is an effort to facilitate the systematic representation of behavior and behavioral phenotypes related to the elderly, with special interest in enabling computational access and reasoning by means of these representations in knowledge-based systems. As a first case of use, we propose the application of ANBO to a specific domain: Teleheath Smart Homes (Latfi et al., 2007). In the context of this work, the role of ANBO is to provide models to monitor cognitive skills and their phenotypes, whose performance usually decreases with age.

The rest of this paper is organized as follows. Section 2 presents the cognitive aging process, its main characteristics and the limitations of traditional methods in assessment and intervention, as well as recent technological advances in relevant methodologies. Section 3 describes ANBO, our proposal to model particularly sensitive cognitive processes over a period of years. Section 4 introduces some of the ontologies related to ANBO because they are reused as part of ANBO as well as sharing a similar topic of interest. Section 5 depicts the way that OSLE and ANBO are integrated while maintaining the independence of both entities. Section 6 evaluates the design and implementation of ANBO. The paper finishes with conclusions and proposals for future work.

2. Assessment and Training of Cognitive Abilities

The global population aged 60 years or over numbered 962 million in 2017 and it is estimated to grow to about 2 billion by the year 2050. In Europe, the population aged 60 years or over reached 183 million in 2017 and the number of older persons is projected to grow to 247 million in 2050 (United Nations and Social Affairs, 2017). Aging is a complex process in which there are cognitive changes affecting a large population. This process is associated with a decline in certain cognitive functions such as attention, episodic memory, working memory, processing speed, and executive functions (Rönnlund et al., 2005; Salthouse, 2010). Generally, cognitive decline has no significant impact on functional independence for older adults, but these difficulties often progress into more serious conditions like dementia (a neurodegenerative illness that is characterized by a decline in mental ability severe enough to interfere with tasks on a day-to-day basis) and Alzheimer's disease (AD). Today, 50 million people are living with dementia and this number will increase to 152 million in 2050, a 204 percent increase which is highly significant (World Health Organization, 2017). Given the overall aging of the population and the cognitive decline associated therewith, there is a great deal of interest in the maintenance of cognitive functions and independent living in older adults for as long as possible. Several studies show that cognitive training interventions and programs can improve cognition in healthy older adults (Ball et al., 2002; Karbach and Kray, 2009).

These studies indicate that neuroplasticity (the physiological capacity of the brain to form and strengthen neuronal connections) is not limited to the early years but extends into old age (Pascual-Leone et al., 2005; Willis et al., 2006). Moreover, cognitive intervention could be beneficial to the treatment of typical and atypical cognitive aging (Engvig et al., 2010) and may reduce the risk of dementia (Verghese et al., 2003). On the other hand, an effective cognitive intervention requires a careful evaluation of cognitive and functional status. That is to say, it is necessary to assess different cognitive operations and how these support everyday functioning. The assessment is typically based on validated hand-written neuropsychological tests or scales, which have shown to be excellent tools for evaluating specific cognitive processes. However, these instruments were not designed to evaluate functional status and the results do not always reflect problems experienced in everyday life (Pugnetti et al., 1998; Mcalister et al., 2016). Thus, these tests present a poor ecological validity, as results from neuropsychological test are not easily generalizable to real-world functioning (Mcalister et al., 2016; Valladares-Rodríguez et al., 2016). In a similar vein, the ecological validity of the actual rehabilitation activities has been questioned, as well as the generalization of new abilities, knowledge and/or skills (Rizzo et al., 2004). More ecologically valid assessment and rehabilitation scenarios are needed. Realistic environments provide high ecological validity because these imply tasks that everyone can find in everyday life. Information and Communication Technologies (ICTs) are tools which could provide scenarios that mimic the real world or are integrated into real-world environments. This would enable evaluation and rehabilitation without the limitations of traditional methods.

3. Description of ANBO

The main purpose of ANBO is not to provide a psychological model of cognition or perception, but a formal representation of such processes. With this in mind, the focus is not on how a cognitive process works, but (i) the conditions under which a process could be triggered, (ii) which results are expected to be achieved at the end of the process, and (iii) which qualities define typical or atypical manifestations of the process. For example, regarding the *visual search*[2] process, ANBO does not say anything about how the process actually happens but rather gives a specification of prerequisites and expected outcomes of this process such as:

- The visual search process is focused on *physical qualities* of objects such *shape*, *size* and *color*.
- A *visual stimulus* is necessary, related to one or more *physical qualities*
- A *visual system* for perceiving the stimulus is necessary.
- Needing too much time to accomplish the task or picking up a wrong object are clues of an abnormal visual search.

[2]visual search, or alternatively visual search, is a type of perceptual task requiring attention that typically involves an active scan of the visual environment for a particular object or feature (the target) among other objects or features (the distractors). Visual Search is defined as an specialization of Visual Behaviour, that is defined as "Behavior related to the actions or reactions of an organism in response to a visual stimulus" in NBO and GO ontologies. Consequently, visual search is a kind of reaction (searching the desired object) as response to a specific visual stimulus (the objects or distractors to be "scanned").

ANBO is designed to support ontology reusability. We embraced the OBO Foundry (Smith et al., 2007) as a design framework. OBO proposes a set of principles including open use, collaborative development, non-overlapping and strictly-scoped content, and common syntax and relations. NBO itself is an OBO Foundry ontology, and our extensions follow these guidelines too.

3.1. Representative elements of ANBO

ANBO processes are made up of a number of constraints, behavior qualities and expected results. Processes explicitly modeled are given below in Table 1:

Cognitive function	ANBO Term ID	Related with
eye-hand coordination	NBO:0000341	perception
visual search	ANBO:0000004	perception
spatial orientation	ANBO:0000001	attention
focused/sustained/alternating/divided attention	ANBO:0000102-3/NBO:0000457-8,60	attention
working memory	NBO:0000180	memory behavior
semantic memory	NBO:0000186	long-term memory
problem solving	NBO:0000297	executive function
monitoring	ANBO:0000101	executive function
planning	ANBO:0000100	executive function
motor coordination	NBO:0000339	praxias

Table 1. Cognitive functions that are defined as behavioral processes in ANBO

Constraints constitute the input of a given cognitive process. These must be satisfied in order to make it possible to trigger the corresponding process. We distinguish between two different types of constraints (see Figure 2):

- Perception. The user has to have the capacity to perceive relevant information from their environment by means of one or more sensory systems. For example, the behaviour *visual search* is triggered in response to *visual perception* by means of a *visual system*.
- Focus. Each process has an environmental event or object of interest which is the focus of that process. For example, a pair of socks that are located in a drawer of a bedside table is the focus of putting clothes away.

A behavioral phenotype is an observed manifestation of a behavioral process. From the point of view of ANBO, a phenotype is one or more qualities of interest with (a) certain value/s as a result of the execution of the given cognitive process under particular conditions(Gkoutos et al., 2005). For example, if the process *visual search* consumes more time than usual (this has an increased duration) or a person becomes disoriented as a consequence of a malfunction of the spatial orientation process.

4. Related ontologies

ANBO expands or reuses a number of ontologies, inter alia, NBO (Gkoutos et al., 2012), PATO (Gkoutos et al., 2005), Uberon (Mungall et al., 2012) and GO (Consortium, 2004).

In this section we provide a brief description of these ontologies and the way that these ontologies are integrated into ANBO. Several of these ontologies are very large. As they are made up of several thousands of classes and relations, a partial export of relevant terms from each ontology is performed using OntoFox[3]. Ontofox is a web-based tool which facilitates ontology reuse, by allowing users to extract properties, annotations, and classes from ontologies and export. them. Ontofox follows and expands the Minimum Information to Reference an External Ontology Term (MIREOT) principle (Courtot et al., 2011).

4.0.1. Neuro-Behaviour Ontology (NBO)

NBO (Gkoutos et al., 2012) is the base upon which ANBO was built. NBO provides formal definitions and systematic representations of the processes involved in behavioral mechanisms and their related behavioral manifestations. ANBO is a specialization of NBO, emphasizing a formal representation of cognitive skills and their phenotypes. Thus, NBO provides the following elements to ANBO:

1. A taxonomy of cognitive processes. Eight of the eleven cognitive processes modelled in ANBO were directly imported from NBO. The other three concepts are defined within the new ontology as specializations of more general NBO concepts (see Figure 1).
2. The formal description of semantic relationships between concepts. By means of these relations is possible to make certain inferences - particularly, which

[3]http://ontofox.hegroup.org

Figure 1. ANBO taxonomy. Shaded squares filled with vertical lines represent processes native to NBO, and those with shaded horizontal lines represent processes which were added specifically to ANBO. Each grey shaded process in directly modeled with ADLs by the combination of ANBO and OSLE.

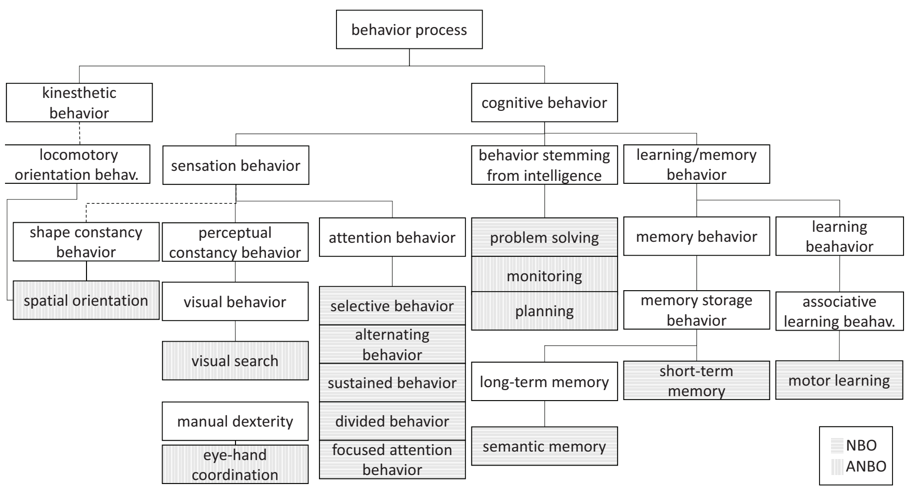
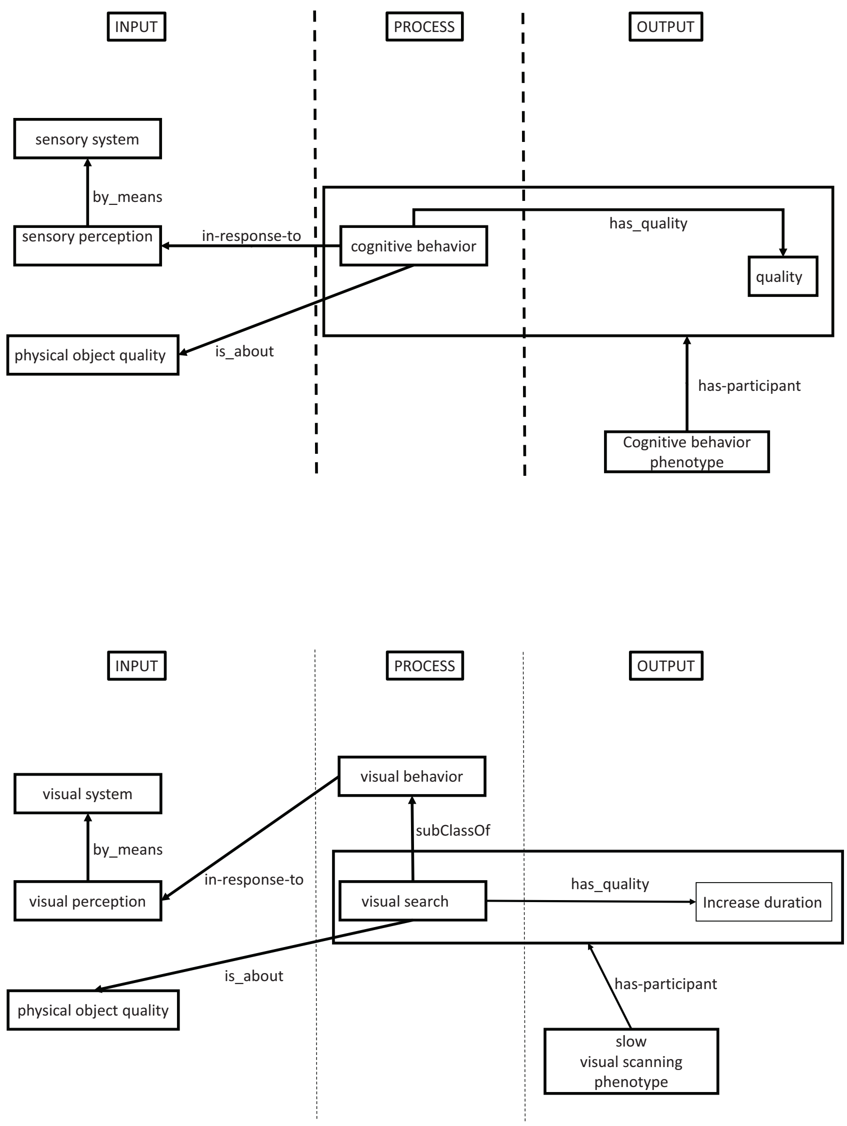


Figure 2. General structure of a cognitive process and an example, visual search process



neurological processes are involved with behavioural processes and phenotypes. NBO defines these relations but does not do so exhaustively. Since the number of classes in ANBO is small relative to NBO itself, we were able to define relationships for all cognitive processes included in the ontology, listed in Table 2. A second highlight to performing inferences is the proposed INPUT-OUTPUT view of the cognitive process. This is always implemented in exactly the same way for every cognitive process. In any case, ANBO follows a similar approach to NBO in formalizing and making computationally accessible every cognitive process that belongs to ANBO (see Figure 2).

Relation	Definition	Example
in_response_to	Between a process x and a process y if and only if x occurs in response to y.	*auditory_behavior in_response_to hearing.* *visual_scanning in_response_to wakefulness*
by_means	A process x occurs by means of a material structure y if and only if x occurs by means of y.	*hearing behaviour by_means auditory system.* *visual_scanning by_means visual behaviour*
is_about	A process x is about some entity y if and only if x is about or directed toward y.	*shape constancy behavior is_about shape.* *visual search is_about physical object quality*
participates_in	A phenotype participates in a behaviour	*slow visual search phenotype participates_in some (has_quality some (increased duration and (towards some visual search)))*
has_input	A phenotype has input a collection of entities with a given property regarding frequency, amount and so on	

Table 2. Relations defined or used in NBO that are relevant for ANBO

4.1. Phenotype And Trait Ontology (PATO)

The Phenotype And Trait Ontology (PATO; Gkoutos et al., 2005, 2009) aims to capture information about phenotypes in any organism. This composes the phenotype by means of two variables: the entity that is observed and the specific characteristic or quality of that entity. Thus, PATO provides a framework for formalizing qualities which enables the characterization of every occurrence of a cognitive process. For example quality, *temporally extended* defined as "a quality of a process which ends later than the natural end time", could affect a *visual search* process that needs more time than usual. A second example is the quality *lacking processual parts* regarding *planning*. PATO defines this quality as "a quality of a process inhering in a bearer by virtue of the bearer's lacking a processual part as specified by the additional entity". The ANBO trait *planning* is a sequence of actions that will achieve a goal. Thus, ANBO makes use of *NBO:has_quality lacking procedural parts* property to express plannings where at least one step is missed.

4.2. Uberon

Uberon, is a cross-species ontology representing anatomical entities organized via anatomical classification reflecting morphology of organs and tissues (Mungall et al., 2012). It is species-agnostic, and includes annotations linking it to species specific (e.g., human or mouse) anatomical ontologies. Thus, it proves a bridge to facilitate cross-species inference. In other words, Uberon provides several levels of detail for anatomical structures, mainly by means of *is-a* and *part-of* relations. The way that ANBO makes use of Uberon is twofold:

- In the same line as some processes defined in NBO, every ANBO cognitive process needs a given anatomical structure as a prerequisite. More concisely, the perception of a stimulus happens due to one or more sensory systems. That is the relation *by_means* draws in Figure 2.
- The user profile, which accesses users' ability to perform ADLs, is completed. As performance of ADLs is used to model cognitive function, and performance relies on a combination of cognitive and physical ability, this ensures that a user is screened to make sure that they are physiologically capable of performing the ADLs that will be monitored.

One advantage of using Uberon is that it is easy to increase the detail of sensory needs linked to a specific cognitive process. The current version of ANBO provides a quite high-level level of anatomical structures that are needed as part of the input of a cognitive process. For example, one user prerequisite that must be satisfied to accomplish *visual search* is that the user *visual system* must be functioning well enough to both visually scan and interpret input from this scanning. But future versions could distinguish in finer detail which part or parts of the visual system, such as *accessory optic system*[4], should be healthy instead of an all-or-nothing approach.

4.3. The Gene Ontology (GO)

GO (Ashburner et al., 2000; Consortium, 2004) provides structured, controlled vocabularies and classifications that cover several domains of molecular and cellular biology. The behavioral process branch of NBO contains a classification of behavior processes which complement and extend GO's behavior process domain. In the same way, ANBO both reuses and expands several classes related to perception, such as GO *visual perception*, *auditive perception* and ANBO *hand proprioception*, which extends GO *proprioception*.

5. A case of use: Ontology SmartLab Elderly (OSLE) and Telehealth Smart Home

The first example of an application of ANBO is to give support to the hypothesis that it is possible to infer cognitive decline by means of performance of daily activities. It is important to note that the objective of this section is not to provide evidence of the hypothesis directly but to validate ANBO by applying it in a specific domain, more concisely the Telehealth Smart Home (TSH). The rest of this section is structured as follows: we briefly introduce the domain where ANBO is applied, TSH. Then we describe Ontology SmartLab Elderly (OSLE), our own ontology integrating with TSH technology. Finally we show how ANBO and OSLE are integrated by means of a number of SWRL translation rules. SWRL is a rule language defined to complement OWL functionality (Horrocks et al., 2004).

[4] According to the Uberon definition, *accessory optic system* as "subdivision of visual system that processes movements of images across the retina and regulates the movement of eyes to keep the image stable"

5.1. Telehealth Smart Home and related studies

Telehealth Smart Home is defined as an adequate model of a smart home designed to care for someone with loss of cognitive autonomy (Rialle et al., 2002). Under this view, a model for taking care of an elderly person suffering loss of cognitive autonomy is proposed by Latfi et al. (2007). They propose seven ontologies that cover several relevant domains associated with the task such as *PersonAndMedicalHistory* or *BehaviourOntology*. Then a number of Bayesian networks that are part of the activity recognition are initiated by means of the instances of the ontologies. These Bayesian networks are used to recognize the activity the patient is probably performing. They are also involved in the learning process of the life habits of the Telehealth Smart Home occupant. As a consequence, they defined a a hierarchy of Bayesian networks which is closely related to the hierarchy of activities. At the lower level are specialized networks devoted to the recognition of simple activities such as the ones which can take place in the bathroom in front of the wash basin. The structure of these networks is defined using the instances of the corresponding ontologies.

In a similar way, Nachabe et al. (2016b,a) propose *OntoSmart* which is focused on monitoring elderly people's activity at home by means of a a wireless sensor network attached to both the body of the patient and sensors/actuators related to ambient parameters and home appliances. Then they implement rules in order to detect and notify atomic activities such as "the patient is standing" or abnormal values related to health alerts such as a heart attack or stroke.

Another example is AGNES (Peter et al., 2013), a system that monitors well-being (the person is happy or unhappy), activity (the person is physically active, very active or resting) and presence (the person is at home) by using several sensors and devices of common use such as smart watches, mobile phones, ambient displays and web cams. This information is then relayed to selected members of the social network of that person.

Hong et al. (2009) proposes an ontology for activity monitoring of daily living aimed at the elderly and disabled. The interaction with objects and movements involved in an activity are recorded by associated sensors which send signals to the central management system for processing. Every sensor signal is attached to a context that is part of an activity of interest. The interrelationships among sensors, contexts and activities is represented by a hierarchical network of ontologies where every node is a sensor, a context or an activity. In addition, it is possible to represent dependencies among nodes by means of AND and OR arcs. Similarly, it distinguishes compulsory, optional and compound nodes.

Finally, González-Landero et al. (2019) propose a mechanism of measuring memory with a "smart cupboard", a cupboard with three sensorized doors with magnetic door sensors. The main goal was to have a device able to assess the memory in a familiar environment without requiring additional effort from the user. For this end, three algorithms are proposed to determine when a user finds an item, and when the user searches for an item without success: the first case is that the user finds a certain item in the first attempt. The second case is that the user finds a certain item in a certain number of attempts. The last case is the one in which the user did not find the item.

5.2. Ontology SmartLab Elderly (OSLE)

OSLE is our proposal to model activities of daily living (ADL). OSLE explicitly represents both activities as a sequence of predefined steps and activities without a specific structure, just a sequence of actions that happens in a given time window. The key differece between both types of activities is that, for the first case, the system "knows" what is the objective and structure of the activity. For example, washing dirty laundry. This is a knowledge-based approach, and OSLE follows the work reported in Hong et al. (2009), briefly introduced previously. In this way, OSLE is made up of sensors, contexts that are the interpretation of sensor readings, and activities that are defined as a group of contexts and/or other activities. For the second case, the task that is accomplished by the user is not modeled as part of the ontology. Activities are not described, but the registration of the sensors and the order in which every sensor activation happens, although such activities are not necessarily part of a predefined process hard coded in the ontology. It is a data-driven approach such as is proposed in Salguero and Espinilla (2017), allowing flexible annotation to the ANBO/OSLE system.

5.2.1. Implementation of OSLE

OSLE is implemented as a specialization of Ontology for Biomedical Investigations, OBI (Bandrowski et al., 2016; Peters et al., 2009). OBI is part of the OBO Foundry which include NBO, GO and PATO. As a consequence, combining OSLE and ANBO is a relatively easy process (see section 5.2.4).

OSLE as an extension of OBI distinguishes between the specification of a plan (*obi: plan specificaction*) and the *realization* of that plan (*obi: planned process*) once this plan is *concretized*. As a specialization of these concepts, OSLE defines *osle:ADL specification* whose realization is achieved by means of ADL processes. At this point, OSLE defines a plan specification as a sequence of *osle:ADL specification step*s. In order to declare each step, a *osle:context* is required which is attached to a given *osle:sensor* and may be a position in the sequence of steps. Finally, a *osle:daily living action* is the register of a context that is triggered as a consequence of the activation of a sensor in a given time-stamp. Eventually, a *osle:daily living action* is attached to *osle:ADL specification step*. An overview of OSLE is depicted in Figure 3.

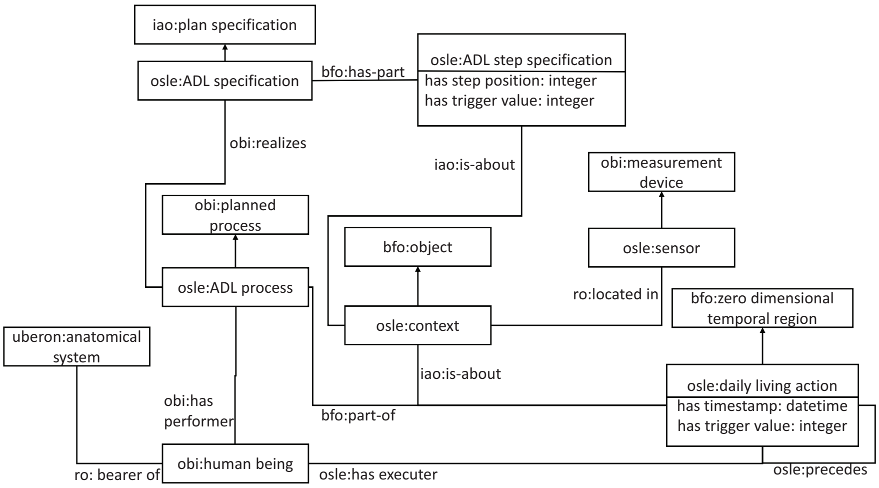
5.2.2. Creating activities in OSLE

In favour of greater clarity, we include the sequence of steps to be followed to both create a new daily living activity specification and register occurrences of such activity or just sequences of sensor readings (contexts) over the course of the day:

Defining a new type of activity

1. Create a new activity (*osle:ADL specification*). For example, *clean dirty clothes using the washing machine*
2. Create contexts as needed (*osle:context*). For example, *washing machine door*
3. Declare sensors as needed (*osle:sensor*) and attach them to the corresponding context (*obi:part of* property). For example, sensor *D09* is attached to *washing machine door*.

Figure 3. Ontology SmartLab Elderly class diagram.



4. Define the sequence of activity steps (*osle:ADL step specification*). Every step is the activation of a given context with a specific value related to an activity. Optionally, it is possible to include the expected order of the step. For example. step *a_cdc step 2* is the second step of activity *clean dirty clothes using the washing machine* and it defines that the value of this context must be *open* (the person opened the door of the washing machine).

Recording the occurrence of an activity

1. Declare the activity performer if it is not previously defined (mp:human being instances)
2. Makes concrete the activity to be performed (*bfo:specifically dependent continuant obi:concretizes osle:ADL specification*)
3. Declare a new *osle:ADL process* as the realization of the concretion of an activity
4. Record every daily living action performed by a *mp:human being* into a sequence of actions over the course of a period of time.

5.2.3. Instance of OSLE

At this moment, we have modeled a smart home equipped with 21 sensors (see Figure 4). All of them have been calibrated by repeating every action 50 times and noting down the number of false readings for each sensor. Since these sensors are quite straightforward to use, we have found no fails in our readings. By means of these sensors we have defined 15 different ADLs: *Clean dirty clothes, Take prescribed medicine, Make breakfast, Make lunch, Make dinner, Have a snack Watch television, Go home, Play a video game, Brush your teeth, Use the toilet, Do the dishes, Change clothes* and *Go to bed*. It is important to remark that the smart home depicted in Figure 4 is an artificial environ-

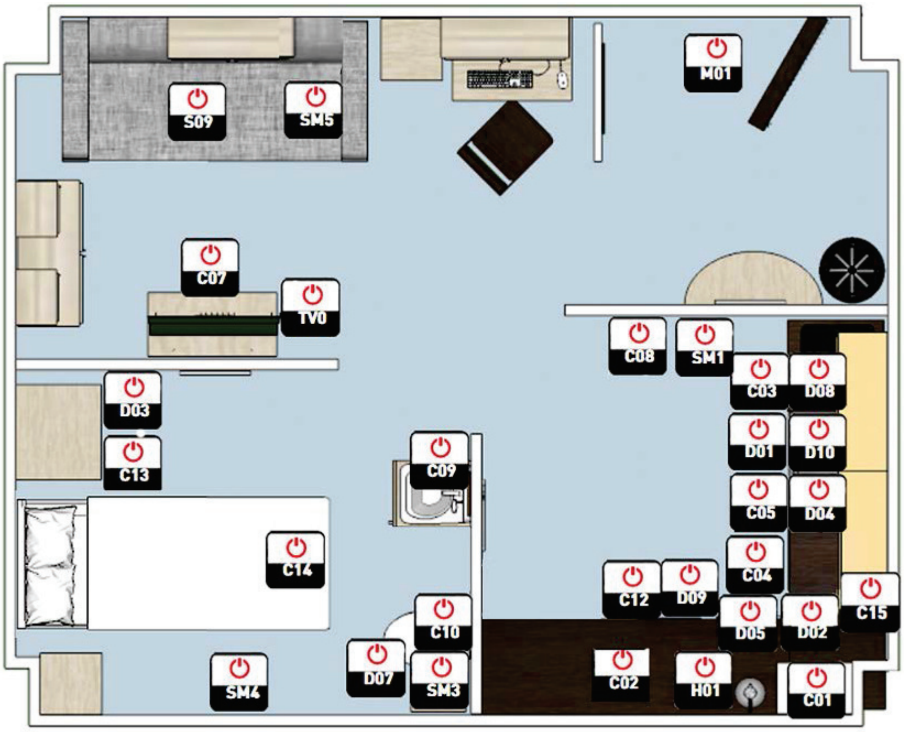


Figure 4. Sensors map in SmartLab: door(M01),TV(TV0), kitchen movement(SM1), motion bathroom(SM3), motion bedroom(SM4), motion sofa(SM5), refrigerator(D01), microwave(D02), wardrobe clothes(D03), cupboards cups(D04), dishwasher(D05), top WC(D07), closet(D08), washing machine(D09), pantry(D10), kettle(H01), medication box(C01), fruit platter(C02), cutlery(C03), pots(C04), water bottle(C05), remote XBOX(C07), trash(C08), tap(C09), tank(C10), laundry basket(C12), pyjamas drawer(C13), bed(C14), kitchen faucet(C15), pressure sofa(S09)

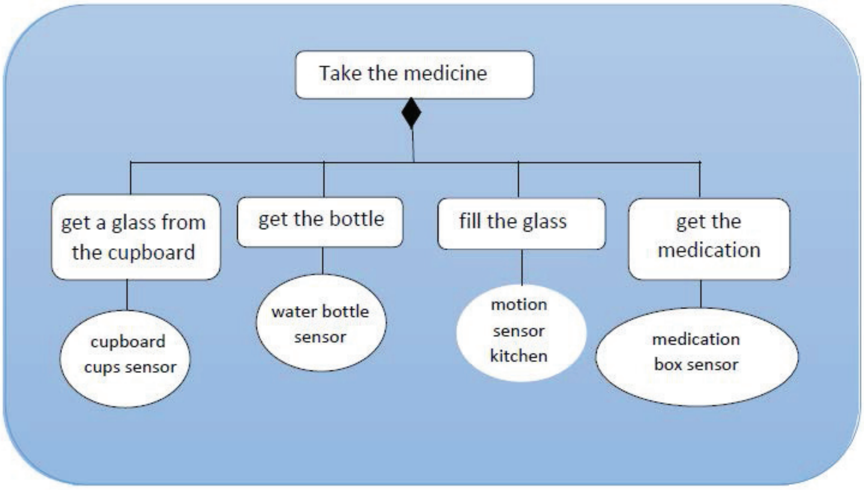
ment that is suitable in order to test the proposed implementation for each ADL. In this way, we have instantiated the proposed ADLs in order to check that, given an ADL, (i) the ADL is correctly identified and (ii) there is not performance issues. For this end, the current prototype has been executed in the main node of a cluster[5] that is made up by 2x Intel(R) Xeon(R) Silver 4210 CPU @ 2.20GHz processors, 96 GB DDR4 @ 2933 Mhz of memory and 60TB of storage. We have checked that ADLs are recorded in real time with no noticeable delay.

5.2.4. Integration of OSLE and ANBO

The end of the integration of OSLE and ANBO is to grasp the relationship between ADLs and cognitive decline associated with the elderly. For example, cooking a french omelette implies the activation of a number of cognitive processes such as is depicted in Figure 6. Even though neither our smart home installation nor OSLE provide the level of detail needed to detect every step of this example, it highlights the potential of integrating

[5]The complete description of the hardware is available at https://www.ujaen.es/centros/ceatic/servicios/supercomputacion/cluster-ada [11-01-2020]

Figure 5. Example of an activity. Notation is following Yao et al. (2005): squares are contexts and activities, ellipses are sensors and the diamond is an AND connector

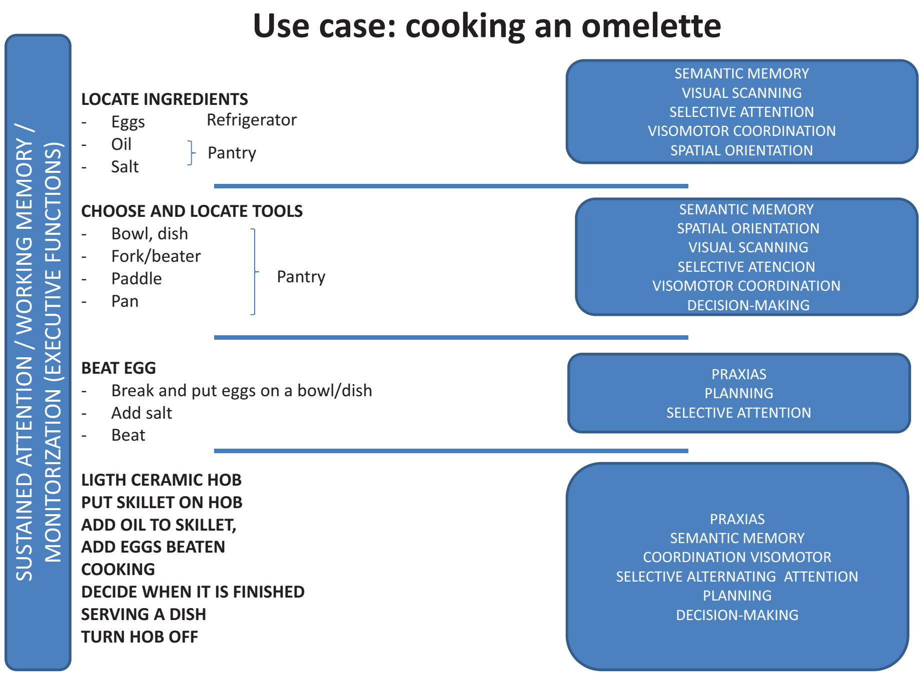


ANBO and OSLE. Our working hypothesis is that more simple or general activities such as choosing the correct medication in the medicine box or cooking are suitable for detecting some clues or issues regarding cognitive processing. The activities that are currently monitored in SmartLab are shown in Figure 4. For example, activity *take a medicine* defines that is necessary to fetch the correct medicine from the medication box. Whether the correct medicine is chosen or not is a clue about the performance of visual search or working memory processes. Therefore, the aim is to give support to this type of reasoning by activating ANBO concepts as a consequence of events or qualities of both environment and user profile registered in OSLE. From this point of view, the integration of ANBO and OSLE is a matter of interpretation of OSLE events as ANBO processes. This approach is implemented as follows:

- The OSLE source is sensor readings. Sensor readings are attached to a given physical context with some sensory qualities. For example, sensor *C05* is attached to a water bottle so when the sensor is activated, it is interpreted as the inhabitant obtained the bottle. In addition, this action has some physical qualities that are suitable for perception by sensory systems such as visual or touch systems.
- Within the ANBO source, every cognitive process requires some prerequisite input layer to be activated. For example, *visual search* (i) is triggered *in response to a visual perception by means of a visual system* of *physical object qualities* and (ii) *is about a physical object quality*, such as morphology or colour of the object or group of objects scanned by means of the vision system.
- The act of obtaining the water bottle is interpreted as a process of type *visual search*, inter alia. In order to accomplish this kind of translation or interpretation, a number of SWRL rules are applied. For the example given, some examples of the rules that are applied are the following (see Figure 7):

```
1.
Name: LightQualityToPhysicalObjectQuality
Comment: Translates a OSLE  context with a visual attribute (color, shape...)
```

Figure 6. Cooking a omelette illustrates the kind of relationship that it is possible to define between both domains, ADL and cognitive functions. Nevertheless, this is a quite ambitious example from the point of view of sensors that are needed to register every action and it exceeds the the current capabilities of our SmartLab

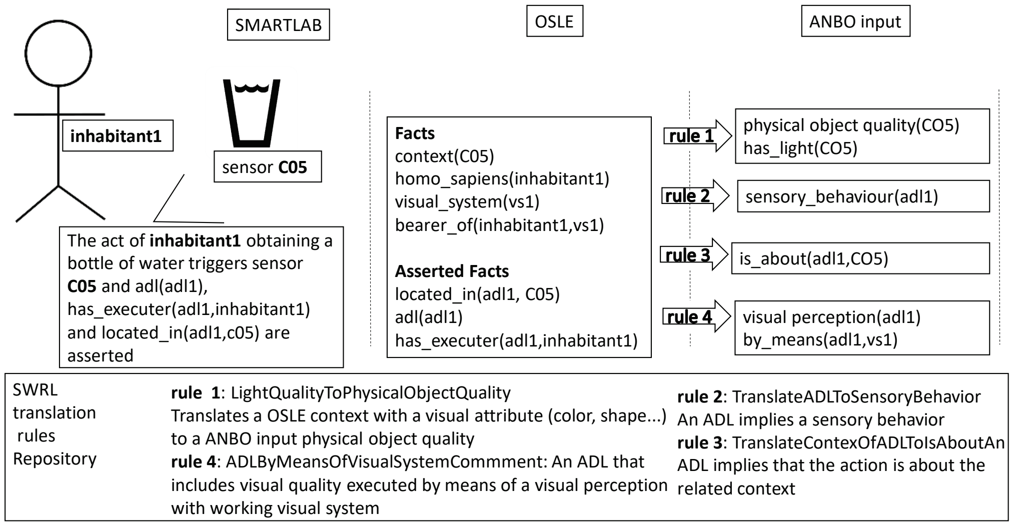



```
       to a ANBO input physical object quality
  OSLE_0000103: context
  PATO_0001241: physical object quality
Rule:
obo1:OSLE_0000103(?c)
^ obo1:uberon/has_quality(?c, osle:light)
->  obo1:PATO_0001241(?c)

2.
Name: TranslateADLToSensoryBehavior
Commment: An ADL implies a sensory behavior
Required to infer: visual behavior
OSLE_0000110: daily living action
  NBO_0000308: sensory behavior
Rule:
obo1:OSLE_0000110(?d)
->obo1:NBO_0000308(?d)
```

```
3.
Name: TranslateContexOfADLToIsAbout
Commment: An ADL implies that the action is about the related context
  OSLE_0000110: daily living action
  RO_0001025: located in
OSLE_0000103: context
Rule:
obo1:OSLE_0000110(?d)
^ obo1:RO_0001025(?d,?c)
^ obo1:OSLE_0000103(?c)
-> nbo:is_about(?d, ?c)
```

Figure 7. An example of SWRL application: an inhabitant gets a bottle of water and it is interpreted as an ADL that is part of the input of a visual search process.



By means of of these rules and others like them, ADLs are interpreted in an incremental way. For example, rule 1 asserts that a glass of water has visual properties, no matter if the attached sensor is triggered or not. Once sensor activation happens, this is interpreted as a visual stimulus. In the case of the elderly person owning a working visual system then the visual stimulus is perceived by means of such a visual system (rule 3). Finally, the combination of rules 1 and 4 allows us to make the inference that a visual search process occurs.

Inferences such as the one depicted above make it possible to ensure independence between the domains concerned: smart homes and cognitive processes. Thus, if a new ADL is defined, it does not include any kind of information about the potential cognitive processes that are implied, just the physical and logical properties of the activity and objects that are part of the new ADL. In the same way, if a new cognitive process is integrated into ANBO, it is defined in terms of input and output parameters, that are attached to an ADL by applying the general SWRL rules.

Moreover, complex tasks that imply several steps allow us to detect divergences between the expected result and the real result, so these divergences could be interpreted as a fail or malfunction of a cognitive process and, in the end, a sign of cognitive decline. For example *osle:take the medicine* requires *get the medication*, *get a glass* and *filling* it. Suppose that the step *filling a glass* never happens, then it is annotated as a fail that is related to cognitive processes such as *anbo:planification* or *ambo:short term memory*. Of course, it is not possible to infer a cognitive decline just because of this divergence between the specification of the ADL and a specific occurrence of the activity. But findings such as not filling the glass when expected are noted down so tendencies of user behavior can be detected by the expert. In other words, the dual ANBO-OSLE is able to comply with requests such as to retrieve a "list of failed ADLs related to planification".

Relation	Definition	Example
part-of	a sensory system is part-of a human	visual system
is-about	an activity step is about a cognitive process	get the medication is about take the medicine

Table 3. ANBO and NBO relations

5.2.5. A note about scalability

Such as is explained above, the proposed architecture has been deployed in a only scenario, the SmartLab, with the main aim of testing and debugging the implementation of ADLs. As a consequence, this says nothing about the scalability of the system towards real environments where the activity of an undetermined number of users is recorded. In any case, the integration of ANBO with OSLE, and particularly the use of reasoning with SWRL, is suitably efficient as to be used in real systems. For this reason, the tractability of the system has been considered in several respects:

- Both ontologies are implemented by means of DL subset of OWL, a standard formalization in Description Logic, maintaining decidability. Moreover, The ELK reasoner can be used for guaranteed classification in polynomial time (Kazakov et al., 2014).
- The ontology design follows OBO Foundry (Smith et al., 2007) recommendations. That is, inter alia, non-overlapping, strictly-scoped content and imports following the MIREOT strategy. These ensure that the ontology is efficient, and that minimal fragments are included from external ontology.
- The possible tree of rules instantiated by the SWRL rules is low in depth and breadth, due to short chaining and a small set of sensors to be triggered together in a temporal period (as the user interacts with the home environment) respectively.

6. ANBO Evaluation

This section complements the validation accomplished by applying ANBO to TLH depicted in section 3, justifying the correctness of ANBO under the view of validation carried out according to the measures proposed by Gómez-Pérez (2001) also together with Lopez and Corcho (2004): consistency, completion, conciseness, expandability and sensitiveness. The following lines justify that ANBO satisfies these criteria:

- Consistency: ANBO, OSLE, the SWRL rules, and all components in combination, are logically consistent. When evaluated using the Hermit reasoner (Shearer et al., 2008), which evaluates the consequences of all asserted axioms in an ontology, no cases of ontology inconsistency, nor class unsatisfiability (classes which logically cannot have instances) were detected.
- Completion: In brief, all that is supposed to be in the ontology is explicitly set out in it, or can be inferred. The way to check completion is by means of the integration with OSLE and the definition of at least one ADL for each cognitive process. Such as is depicted in section 5, OSLE is independent from ANBO and the SWRL are independent from the cognitive processes. As a consequence, every cognitive process is inferred rather than assessed. In addition, as intermediate steps over the course of these inferences, the reasoner obtains instances of ANBO concepts related to sensory stimulus and physical object qualities.
- Conciseness: Again, we rely on OSLE to check this desirable property of the ontology: every class that is explicitly defined in ANBO is instantiated as a consequence of at least one ADL. This proves that every concept is useful. In addition, we have explicitly defined as disjoint classes those that share a common superclass. For example, the whole of the cognitive processes of interest for ANBO are defined as disjoint classes.
- Expandability is related to "the effort required in adding new definitions to an ontology and more knowledge to its definitions, without altering the set of well-defined properties that are already guaranteed"(Gómez-Pérez, 2001). Any necessary expansion of the ontology is a task that is well-defined and homogeneous, since we have carefully defined a template, depicted in Figure 2, such that a new cognitive process is always defined in the same way: (i) extending NBO *cognitive behavior* class and (ii) defining the input and output layers always in terms of sensory and environmental requirement and outcomes. Since new definitions would rely on including and expanding existent NBO concepts, we ensure that descriptions of new cognitive processes can be developed with minimal overhead.
- Sensitiveness relates to how small changes in a definition alter the set of well-defined properties that are already guaranteed. We face this issue both when a cognitive process is added or modified and when ANBO as a whole is integrated with other ontologies such as OSLE. Cognitive processes are independent, and therefore do not require knowledge about other cognitive processes - this means that addition of new cognitive processes and modification of existing processes will not have knock-on effects outside of the relevant semantic locality. The use of SWRL rules as a bridging layer between OSLE and ANBO ensures that details that pertain to particular application uses are not included in the ontology itself, meaning that definitions will not need to be changed to support additional uses. Since the cognitive processes in ANBO make heavy use of well-developed and supported ontologies in the relevant domains, major changes are unlikely to be made, or will be made in such a way that support backwards-compatibility, and a preservation of logical functionality.

7. Conclusions and future work

Given an aging population and associated cognitive decline, identifying factors that may shield individuals from cognitive deterioration is a matter of societal interest. Many studies have attempted to identify ways to detect, reduce and/or counteract the course of cognitive and brain decline. However, traditional neuropsychological methods have some limitations, such as poor ecological validity. In this paper we present ANBO, a framework that builds on well established methodologies in knowledge representation, that can be used as a model of neuropsychological function with respect to ADLs, in order to create a method by which cognitive decline may be detected, and appropriate interventions determined. In addition, we implement and demonstrate this framework, by applying ANBO to Telehealth Smart Homes, allowing us to describe Activities of Daily Living. As a result of such integration, it is possible to make an original interpretation of these activities in terms of cognitive processes their success. The work in describing cognitive processes also has implications in the development of a axiomatisation pattern for cognitive processes, which could be used to normalize axioms in higher level concepts.

The work presented may be continued and extended in many ways. A point of importance in establishing the validity of this method is to run an actual trial involving test subjects, and using the generated data to determine whether neuropsychological decline can be adequately detected. NBO should also be applied to design interventions integrated as naturally as possible into ADLs in order to prevent and/or palliate cognitive decline. There are also plenty of opportunities to increase the coverage of ANBO (i) by including new cognitive processes of interest in the field of the elderly and (ii) by giving more detail. More detailed definitions of cognitive processes would make it possible to be more precise regarding the sensory capabilities required for a given cognitive process, thereby improving the sensitivity of any inferences. The system could also be applied, through development of other SWRL interaction layers, to other ontology-based smart-home systems (as mentioned earlier). In this way, from our point of view, one of the most promising ways to apply this ontology is the implementation of, i.e., a bayesian model in order to learn from the user behaviour so that, in the long term, it enables a kind of cognitive decline alert system when deviation related with the user's behaviour are detected and this deviations are statiscally significant. From this point a view, a isolated fail will no be relevant, but several of then could trigger the alert about a specific cognitive domain decline. It is also our intention to apply ANBO in other domains, such as in cognitive rehabilitation. In effect, the model would be applicable in any domain which seeks to associate physical behaviours with cognitive processes.

Regarding ANBO and OSLE integration, the next step is clear: it is necessary to validate the scalability of the architecture by monitoring a significant number of real homes. Note that it is difficult to replicate the whole SmartLab in every home. For this reason, both a minimum set of sensors and ADLs will be defined. At the moment of writing this paper, task "watch TV" is ready to be implemented in real homes by means of cheap sensors (TV0,C07,So9 and SM5 sensors such as are depicted in Figure 4), and a Raspberry Pi 3b+ plus a 4G communication module (Waveshare Hat SIM7600E) as base gatway. As a second stage will be the validation of the hypothesis that it is possible to identify cognitive decline, more concisely memory decline, by means of the integration of both OSLE and ANBO.

A. URLs of ANBO, OSLE and related ontologies and resources

In this appendix, we list the URLs where the referenced ontologies described in section 3 and 5.2 are available.

Related ontology	Type	Source	Definition
ANBO	Ontology	http://www4.ujaen.es/ dofer/ontologies/ obo/releases/2018-31-07/anbo.owl	Formal model of cognitive processes that are particularly relevant on a day-to-day ba-sis and whose performance usually declines when adults get older
OSLE	Ontology	http://www4.ujaen.es/ dofer/ontologies/ obo/releases/2018-31-07/osle.owl	An ontology related with Telehealth Smart Homes where Activities of Daily Living are recorded
OSLE example	Ontology	http://www4.ujaen.es/ dofer/ontologies/ obo/releases/2018-31-07/ osle_instance1.owl	An instance of OSLE according Smart Lab configuration (see Figure 4 and 5)
ANBO & OSLE	SWRL	http://www4.ujaen.es/ dofer/ontologies/ obo/releases/2018-31-07/trules.swrl	Rules in order to integrate ANBO and OSLE while keeping both ontologies independet
ANBO	imports	http://www4.ujaen.es/ dofer/ontologies/ obo/anbo/external/nbo_import.owl http://www4.ujaen.es/ dofer/ontologies/ obo/anbo/external/nbo_import_mireot.owl	ANBO imports from NBO and related ontologies
ANBO	OntoFox config file	http://www4.ujaen.es/ dofer/ontologies/ obo/anbo/external/nbo_import_mireot.txt	Ontofox input file in order to generate nbo_import_mireot.owl imports
OSLE	imports	http://www4.ujaen.es/ dofer/ontologies/ obo/osle/external/go_import.owl http://www4.ujaen.es/ dofer/ontologies/ obo/osle/external/obi_import.owl http://www4.ujaen.es/ dofer/ontologies/ obo/osle/external/uberon_import.owl	OSLE imports from OBI and related ontologies

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