Designing Memory Aids for Dementia Patients using Earables

Matija Franklin
University College London
London, UK
matija.franklin@ucl.ac.uk

David Lagnado
University College London
London, UK
d.lagnado@ucl.ac.uk

Chulhong Min
Nokia Bell Labs
Cambridge, UK
chulhong.min@nokia-bell-labs.com

Akhil Mathur
Nokia Bell Labs
Cambridge, UK
akhil.mathur@nokia-bell-labs.com

Fahim Kawsar
Nokia Bell Labs
Cambridge, UK
fahim.kawsar@nokia-bell-labs.com

ABSTRACT

Globally around 50 million people are currently living with dementia, and there are nearly 10 million new cases every year. The decline of memory and, with it, lack of self-confidence and continuous confusion have a devastating effect on people living with this disease. Dementia patients even struggle to accomplish mundane chores and require assistance for daily living and social connectedness. Over the past decade, we have seen remarkable growth in wearable technologies to manage our health and wellbeing and improve our awareness and social connectedness. However, we have to ask why wearables are not addressing this fundamental challenge of memory augmentation that threatens our society? Some limited existing work on cognitive wearables for dementia has focused on using images via camera-based life-logging technology. Instead, in this paper, we argue that *earable* - by virtue of its unique placement, rich sensing modalities, and acoustic feedback capabilities, uncovers new opportunities to augment human cognition to address this pressing need to assist dementia patients. To this end, we delve into fundamental principles of cognitive neuroscience to understand what constitutes memory disorder and its symptoms concerning errors in everyday activities. Building on this, we discuss the benefits of earables (in conjunction with smart objects) in modelling activity and intention of dementia patients and providing contextual memory cues. We put forward a guidance system to assist dementia patients with daily living and social connectedness.

CCS CONCEPTS

• **Computer systems organization → Embedded systems**.

KEYWORDS

earables, dementia, cognitive impairment, memory aids

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1 INTRODUCTION

50 million people worldwide live with dementia, and nearly 10 million new cases are reported every year [1]. The loss of memory and, with it, a sense of identity are the most distressing aspects of this disease. Dementia patients even struggle to accomplish mundane chores and require assistance for daily living and social connectedness [1].

Various memory aids have been proposed to help people with dementia and mild cognitive impairments (MCI). The most common examples of traditional methods are post-it notes, calendars, and diaries [2]. Memory assistive technologies with electronic devices are also widely used, such as note-taking on digital devices and intelligent digital assistants (Siri, Cortana, Google Assistant). Recent wearable technologies enabled context-aware, automated intervention by leveraging a variety of sensors. The wearable remembrance agent [25] is a first-kind-of wearable system for augmented memory. It continuously monitors information retrieved from computers such as note files and emails, and provides just-in-time one-line summaries of information relevant to the user's location and time. Hodges et al. presented SenseCam [11], a wearable camera for a retrospective memory aid, which automatically records surrounding events and helps wearers review the recordings and stimulate their memory. DejaView [4] is a healthcare system that infers a user's surrounding contexts with a combination of sensors, including an accelerometer, a microphone, and a camera, and aids recall of daily activities and plans by unobtrusively cueing the user with relevant information. However, the existing work on cognitive wearables has been still limited to be practically used in daily life. The camera-based solutions for memory support require users to carry a bulky device and to make additional attention to the real-time interaction, e.g., with the smartphone or a computer display.

Here, we ask how wearables can help dementia patients live a better and more independent life. To answer the questions, we focus on the everyday tasks of dementia patients, such as tea-making, getting dressed, and pill-taking, which adults with dementia are known to struggle with. This inability to carry out activities of daily living is associated with a diminished quality of life, poor self-esteem, anxiety, and social isolation [3].

In this paper, we argue that *earable* - by virtue of its unique placement, rich sensing modalities, and acoustic feedback capabilities uncovers new opportunities to augment human cognition to address this pressing need to assist dementia patients. To this end, we delve into fundamental principles of cognitive neuroscience to understand what constitutes this memory disorder and its symptoms concerning errors in everyday activities. We first give a primer on dementia, along with a taxonomy of cognitive issues related to dementia as well as the characteristics of patient errors that result from memory impairments. Then, building on these findings and their implications, we discuss the benefits of earables (in conjunction with smart objects) in modelling activity and intention of dementia patients and providing practical and contextual memory cues. We also put forward a guidance system to assist dementia patients for their daily living, and social connectedness.

2 COGNITION AND DEMENTIA: A PRIMER

We begin by delving into principles of human cognition, cognitive decline, and its relationship with dementia.

Cognitive decline: Age-associated cognitive decline is the inevitable process of normal, non-pathological neurological ageing [16]. From early adulthood, processing ('thinking') speed, working memory, reasoning and executive function all start to decline [5]. The rate of 'normal' brain ageing and the associated cognitive decline depend on many factors, including genetics, general health, lifestyle (e.g., diet), medical disorders, and biological processes such as inflammation. Dementia and mild cognitive impairment (MCI), on the other hand, are relatively rare in that most older people do not develop dementia; with current estimates suggesting that less than one in five people over the age of 80 have dementia [24].

Dementia and cognitive decline: Dementia is a syndrome that is associated with a deterioration of memory and thinking, and an overall decline of cognitive abilities at a greater pace [20]. Symptoms include problems with planning and doing tasks in the right order, memory loss, mood and personality changes, and confusion. Dementia is diagnosed when these symptoms cause problems with activities of daily living (ADLs) to the point that a person cannot live independently. Dementia is not a singular disease but associated with multiple symptoms of memory loss, thinking and communication issues. Alzheimer's disease is the most common type of dementia, making up 60-75% of the total patients [24].

Dementia and MCI are not a part of normal brain ageing, but rather, diagnosable conditions. MCI affects 5-20% of the population aged 65 and over [24]. It disrupts the same cognitive functions affected by 'normal' brain ageing - processing speed, working memory, reasoning and executive function - but to a greater extent. Common functional memory problems reported by people with MCI include forgetting names, numbers and passwords, misplacing things, issues with remembering what was said or decided upon, and keeping track of commitments and intended activities. Thus, MCI does not fully prevent independent living and some cases are treatable. One in 6 cases of MCI progress to dementia within a year.

Dementia and cognitive functions: To understand the cognitive functions affected by dementia, we offer a short overview of cognitive domains and their implications associated with dementia.

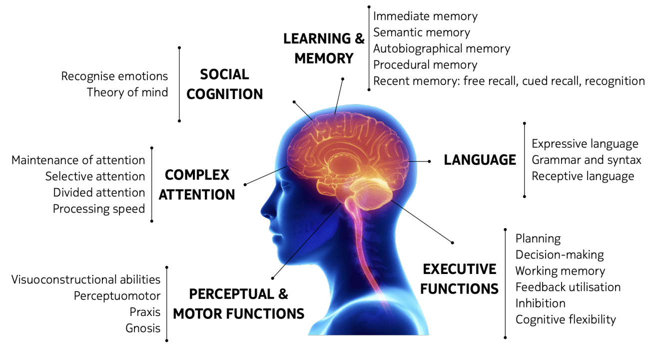

Figure 1: Cognitive domains and corresponding functions associated with dementia and mild cognitive impairment

The Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (American Psychiatric Association, 2013) - the taxonomic and diagnostic tool used by the American Psychiatric Association for psychiatric diagnoses - identifies six cognitive domains associated with dementia [12] as illustrated in Figure 1.

- **Complex attention:** This domain covers the maintenance of attention, selective attention, divided attention and processing speed. Disruptions to this ability mean that normal tasks take longer, especially in the presence of competing stimuli.
- **Executive functioning:** This domain reflects the functions concerning planning, decision-making, working memory, feedback utilisation, inhibition and cognitive flexibility. Disruptions to this ability include difficulties with multi-stage tasks, multi-tasking, following directions, organising, planning and keeping up with shifting situations and conversations.
- **Learning and memory:** This domain covers functions of *immediate memory* (e.g., repeating a list of digits), *semantic memory* (e.g., remembering facts), *autobiographical memory* (e.g.., remembering personal events), and *procedural memory* (e.g., recalling skills required to carry out procedures), as well as *recent memory*, which includes free recall (e.g., recalling as many things as possible), *cued recall* (e.g., recalling as many things as possible from a specific category) and recognition. Disruptions to this ability include difficulties recalling recent events, losing track of one's own actions, misplacing objects and repeating oneself.
- **Language:** This domain represents *expressive language* (i.e., fluency in speech), *grammar and syntax*, and *receptive language* (i.e., comprehension). Disruptions to this ability include use of wrong words, grammatical error, word-finding difficulty and difficulties with comprehension of spoken or written language.
- **Perceptual-motor and visuospatial function:** This domain covers *visuoconstructional abilities* (e.g., draw, assemble furniture), *perceptuomotor* (e.g., insert puzzle piece into appropriate slots), *praxis* (e.g., ability to mime gestures) and *gnosis* (e.g., recognises faces and colors). Disruptions in this ability can lead to patients getting lost in familiar places, and finding it difficult to use familiar tools and appliances.
- **Social cognition:** This domain represents the ability to recognise emotions and to have a theory of mind (e.g., considering another person's thoughts and intentions). Disruption to this

ability can lead to a loss of empathy, loss of judgement and inappropriate behaviour.

Dementia patients experience disruptions to these cognitive functions at varying degrees depending on the stage of the disease. However, the common symptoms, irrespective of the decline of specific cognitive functions in dementia patients, are errors in everyday functioning. Naturally, understanding and designing interventions aimed at addressing these symptoms are active research areas. We consider this aspect of understanding and designing interventions for the symptoms is where wearables, and in particular *earable*, can play a critical role. To this end, in the next section, we delve into error patterns typically demonstrated by dementia patients as a structured and systematic understanding of these patterns will provide us with the proper foundation for applying earable-based assistive solutions.

3 UNDERSTANDING ERROR PATTERNS OF DEMENTIA PATIENTS

Areas of cognition that are disrupted by dementia produce well-known patterns of errors. These include calculation, memory of past events, prospective memory (e.g., remembering to attend an upcoming appointment) and the sequencing of complex behaviour [15]. In this section, we reflect on several past studies to systematically identify a set of error patterns associated with dementia patients.

Action coding for error identification: To understand and systematically categorise the different errors produced by dementia patients, researchers have used the action coding system - a method for coding the actions of patients [28]. Here, A1 transcripts provide low-level descriptions of a patient's interaction with the environment that allowed the errors to be identified. There are four different types of actions: move, alter, take, and give. A2 transcripts are procedures within the A1 actions, which can be used to identify errors within the transition between A1 sub-goals. In other words, the flow between different actions can be analysed as well as the degree of overlap between different actions.

A review of research using the action coding system identified eight common dementia patient errors that occur during activities of daily living (ADL), for instance, making a hot drink. The errors - six types of error and two types of incoherent action [28] included:

(1) Place substitution (e.g., putting tea in cereal)
(2) Object substitution (e.g., apple juice added to the cup of tea)
(3) Drinking anticipation (e.g., drinking tea before it is prepared)
(4) Omission errors (e.g., pouring in water from the kettle before it boiled)
(5) Instrumental substitutions (e.g., stirring the tea with a knife)
(6) Faulty execution (e.g., not fully opening a sugar packet)

The incoherent actions were:

(1) Independent acts (e.g., picking up a random item and then putting it down again)
(2) Toying behaviour (e.g., making random gestures with objects with no apparent aim to the action).

A point of note here is that these actions and their transitions can be modelled with activity recognition capabilities afforded by wearables today. We reflect on this in the latter part of this paper.

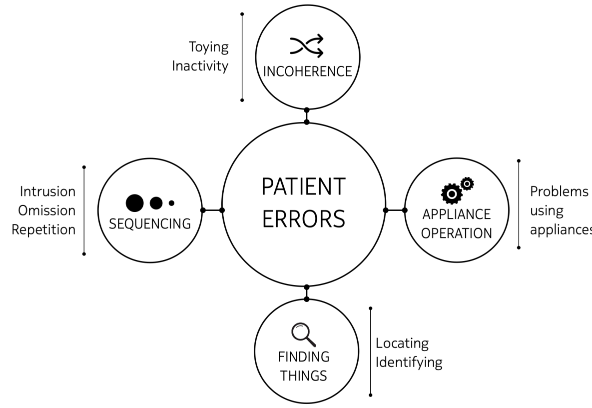

Figure 2: Dementia patient errors in the presence of interventions/active assistance during activities of daily living

Multi-Level action coding for error identification: Researchers have also used the Multi Level Action Test (MLAT) - a standardised test of action disorders - as well as the Naturalistic Action Test (NAT), which is a shortened version of MLAT [26, 27]. In MLAT, the patient being assessed is asked to carry out a task, such as making a slice of toast with jam and butter or wrapping a present. The task is then completed in one of four conditions marked by different levels of difficulty. The first level is *solo basic* where only the required materials are presented. Second is *solo-distractors* where some functionally related items are also presented next to the required materials. Third is *dual-basic* where items for a primary task are presented next to items of another specific task (e.g., making a slice of toast and preparing a cup of tea). Finally, the *dual-sear* condition involves some of the materials which are located in different parts of the room, next to other task-irrelevant items. Research using MLAT has identified eight common dementia patient errors [26].

(1) Omission, which is failing to perform an action
(2) Sequence error, including anticipation-omission (i.e., skipping a necessary step to perform another step), reversal (i.e., reversing the ordering of two steps) and preservation (i.e., performing the action more times than intended)
(3) Object substitution, which is using the wrong object to perform an action
(4) Action addition, where an additional unnecessary action is performed
(5) Gesture substitution, which is performing an action in an uncommon, usually more difficult way
(6) Grasp-spatial misorientation, which involves holding an object in an incorrect way
(7) Spatial misorientation, which is sort of error stemming from misjudgment of size, amount or any similar measure of quantity
(8) Tool omission is using the wrong object to perform an action

Altogether, research finds that omission errors are the most frequent error types, followed by sequence errors [9]. Further, the presence of distractor objects predicatively increases the occurrence of omission and substitution errors.

Error patterns in the presence of interventions: A more ecologically valid study investigated people with dementia performing

ADLs that they themselves identified as important in their own kitchens, including making a cup of tea or coffee [28]. The study tried to assist patients using five levels of prompting: 1) a verbal prompt of the end goal, 2) a verbal prompt of the sub-goal, 3) a verbal prompt of the action, 4) a verbal prompt of action and pointing, 5) performing the action for them. Based on the results, the study concluded four broader areas of error: sequencing, finding things, operation of appliances, incoherence [28] as depicted in Figure 2.

- **Sequencing** errors included intrusion, whereby an inappropriate action is performed from a different activity that prevents the completion of the current activity; omission, whereby a patient misses an action that is required for completing the activity and accomplishing the end goal; repetition, whereby a patient unnecessarily repeats an action that prevents the completion of the activity.
- **Finding things** errors included locating - errors in finding items that are out of view - and identifying - selecting items that are in view.
- **Operation of appliances** errors were problems of using different appliances such as the kettle or toaster.
- **Incoherence** errors included toying - performing random gestures with items with no apparent goal - and inactivity - not performing any action at all.

This systematic analysis of error patterns exhibited by dementia patients provides the foundation for designing intervention solutions with wearables. However, it also expose the requirement for intervention beyond on-body augmentations, i.e., instrumentation of patient environments to offer situated assistance.

Intention-action Gap: The uniformity of results across patients has led researchers to argue that the different types of error all result from a disruption to a cognitive process responsible for goal-directed behaviour [28]. To this end, Norman et al. proposed *the contention scheduling model* - a model of action error - that explains how this disruption would occur [22]. The model proposes that the pathological weakening of top-down activation from a supervisory attentional system means that the contention scheduling system responsible for choosing action schemas is disrupted and does not work the way it should. Bottom-up activation externally from environmental triggers and internally from associated action schemas result in actions that do not follow the intended goal. This produces an intention-action gap in dementia patients.

Implications: We can draw several important implications that emerged from these studies in the design of memory aid applying pervasive technologies to support dementia patients. The contention scheduling model essentially exposes the critical challenge, i.e., to reduce the gap between patient's intention and corresponding action by modelling patient's activity and interaction with the physical world and situational context. This understanding then further be utilised to design interventions applying implicit or explicit memory cues. The error patterns highlight the scope of these challenges quite appropriately.

On **activity modelling**, it is imperative to understand: 1) patients' motion-induced physical activity and gesture, 2) the state and identity of the physical object that a patient interacts with to accomplish the intended task, 3) the exact interaction dynamics concerning the physical object in context.

On **intention modelling**, it is critical to understand the patient's overall objective to derive a plan applying causal reasoning grounded on predictive modelling of a patient's past actions for the same purpose. This aspect uncovers interesting modelling challenges and demands thoughtful mitigation strategy both for directive and corrective guidance.

On **designing memory cues**, we see opportunities in two different dimensions. First, it is imperative to create implicit memory cues, e.g., voice prompts, just-in-time visuals, to direct and correct patients' actions. Second, we also see opportunities to augment physical objects with awareness technologies (sensors and actuators) to augment their functional capabilities to participate in a patient activity in a proactive way.

In the next section, we discuss how we can apply these implications to design memory aids for dementia patients.

4 EARABLE AS MEMORY AID

In the previous sections, we offered a concise overview of cognition decline, its relationship with dementia, and its implications on dementia patients concerning errors in ADLs. We also identified three primary challenges in designing memory aids to support dementia patients in mitigating these errors. In this section, we want to posit that *earables*, together with smart objects, provide the proper foundation for designing assistive guidance for dementia patients. Grounded on *contention scheduling model*, we learned that reducing the gap between intended objective and corresponding actions is one of the critical facets to assist dementia patients. Taking a deeper view of this facet, we have identified three key dimensions: activity modelling, intention modelling, and effective memory cues that can collectively mitigate erroneous actions. Earables today come with rich sensors, including inertial measurement unit (IMU), microphones, Bluetooth Low Energy (BLE), and in some instances, optical sensor (PPG), core body temperature sensor, and electrodermal activity (EDA) sensor. These sensors and their placement in the ear collectively offer us unique opportunities to observe and understand internal (biomarkers) and external contexts around a human body and offer us privacy-preserving, intimate, and subtle feedback capabilities through synthesised speech, music, and acoustic cues. These capabilities are critical to all three dimensions we listed before.

Activity modeling: We can recognise upper body movements, such as head and neck activities [6, 21], facial activities and expression [18], and whole-body movements, i.e., walking, standing, falling, etc. [21]. These motion primitives are vital artefacts to understand a patient's motion-induced physical activities and gestures. Note that modelling all these context primitives, especially around the head, is not possible with other wearables. The acoustic channel of an earable enables us to understand environment ambience and audio events [19, 23], thereby modelling a patient's proxemic, social context as well patient's interaction with physical objects [10]. Combining these primitives and their thoughtful synthesis is key in modelling patient activities and creating digital memories through encoding for future recall.

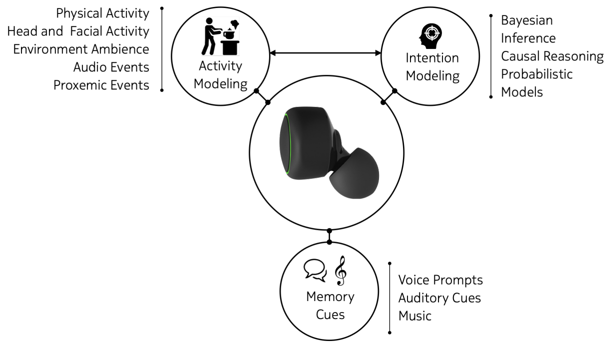

Figure 3: Unique opportunities of earables with context primitives from activity and intention modelling, and acoustic feedback to design effective memory cues

Intention modelling : These context primitives also hold the key to causal reasoning to understand the patient's intention. Of course, a patient can use explicit instructions, such as *"I want to make a cup of tea*, or *"I want to have my medication"* to express her intention. However, we argue these context primitives are the causal link to decipher a patient's intended action. For instance, head orientation and gaze indicate an activity location where a patient might be interested; picking a particular object with a distinct soundscape or moving to a specific direction might tell a patient's intention to a broader activity. Causal models that could draw inferences about the expected activity in a particular location can eliminate or reduce confusion that a dementia patient experiences. We advocate further research on Bayesian techniques, causal inferences, and probabilistic models grounded on these context primitives to model patient's intentions. In addition, we also see opportunities to model the errors that a patient encounters to predict potential divergence from an intended activity. Using different context primitives, an earable can accurately represent a patient's situational context and erroneous actions. We can later exploit these actions to identify an early indication of a potential mistake.

Memory Cues: Finally, earable offers a unique opportunity to provide memory cues using its acoustic channel. Literature on human memory demonstrated that auditory stimuli remain in our sensory registry for at least 4 seconds (compared to 1 second of visual stimuli). This aspect is very critical for dementia patients due to their declined cognition, as we have explained before. Given the privacy-preserving and intimate placement and delivery mechanism of earables, synthesised voice prompts, auditory cues, and music can be designed as memory cues to guide dementia patients. This feature is a big differentiation attribute of earable compared to other on-body wearables with memory aids for dementia patients.

5 SMART OBJECT AS MEMORY CUES

Earables can offer implicit memory cues; however, as discussed earlier, modelling the activity of a dementia patient also demands an accurate understanding of object interaction. Over the past decade, we have seen remarkable progress in smart object research in which everyday objects are instrumented with awareness technologies, i.e., sensors and actuators, to offer value-added functionalities beyond their primary established purposes [7, 8, 13, 17]. We consider these

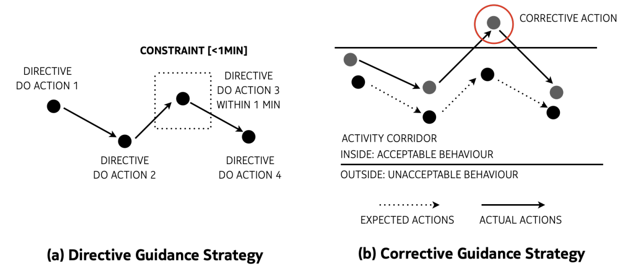

Figure 4: Two different strategies to guide dementia patients

objects in concert with earables to provide the best foundation for designing memory aids for dementia patients. We envision physical objects that can understand their state of use and can proactively activate to offer auditory or visual cues (e.g., playing a tone, voice prompts, or illumination) to guide the activities of dementia patients and offer the activity traces that we can leverage to build a better causal reasoning model to understand a patient's intention.

6 AMBIENT GUIDANCE SYSTEM

Building on the activity models, intention models, and memory cues we discussed in the earlier section, here we present a blueprint of an ambient guidance system combining earables and smart objects as memory aids for dementia patients. Our system borrows principle from Situated Flows [14], first reported by Kawsar et al. to design an activity-aware situated guidance system for workers in a structured workplace. A situated flow (flow, for short) is a high-level declarative abstraction for modelling real-life processes and human activities. It consists of a set of actions glued together by a plan (a set of transitions), which defines how actions should be performed to achieve some goal under a set of constraints. In the context of this work, a situated flow essentially describes the prescribed steps of an activity that a patient is interested in accomplishing. These flows can be predefined or derived from the patients' past actions while completing a task.

Our ambient guidance system consists of two components: guidance strategies for deciding which information should be accessible and when, where, and how it should be presented in the patient's immediate environment using earables and smart objects. Situated flows represent context-specific prescriptions for how activities and tasks are supposed to be done or how a dementia patient operates an appliance. Memory cues with earables and smart objects make it possible to expose activity and task information to a patient. However, to effectively guide a patient, it is not enough to present a patient with every single step. Practical guidance requires a guidance strategy that defines:

- Which tasks and activities are exposed to a patient.
- When and where guidance information is presented.
- How to present guidance information with memory cues.
- How to cope with situations in which a patient does not follow the guidance.

In order to cope with such disparate requirements, we propose two levels of generic guidance strategies.

Directive guidance: Directive guidance (Figure 4(a)) is a strategy that presents a patient with just-in-time notifications (directives) of the following activities to be done. To be precise, directives are generated and presented to a patient before an activity has to be performed. For example, in a medication context, before and during taking medicines, it is beneficial to provide an updated (if any) instruction to the patient.

Corrective guidance: Corrective guidance (Figure 4(b)) is a strategy that assumes that a patient has a sufficient understanding of what she has to do and that she does not require constant reminders. Instead, this strategy only presents a patient with guidance information when the system detects significant deviations from the plan. This aspect is visualized in Figure 4(b): an activity corridor defines how much an actual activity may deviate from the one prescribed by the activity plan. If an action falls outside the activity corridor, the system issues corrective feedback to inform patients of the deviation and motivate the patient to follow the plan as described. For example, in a tea-making scenario, if a patient accidentally picks a salt canister instead of a sugar canister, the guidance system kicks in with a reminder. The corrective plans can be dynamically generated from the activity model and current activity state.

One may argue that, instead of earables, the proposed guidance system can be built with cameras installed in care homes and video analytics solution. It might be able to provide higher accuracy of activity and intention modelling, but cannot provide instant, contextual memory cues as effectively as earables. Also, they are inherently limited to be used in everyday situations due to privacy invasion, narrow spatial coverage, expensive hardware cost.

7 CONCLUDING REMARKS

Dementia is a threat to our aging population. Cognitive deficits and a loss of self-identity of dementia patients fundamentally challenge our society to react and rethink. Wearables, and in particular earables, offer a unique opportunity to contribute to the ongoing effort in addressing this societal challenge. The present article aims to provide theoretical and methodological insights that provide a solid foundation for wearable technology. We first gave a primer on dementia, along with a taxonomy of cognitive issues related to dementia as well as the characteristic patient errors that result from memory impairments. Then, building on these findings and their implications, we discussed the benefits of earable (in conjunction with smart objects) in modeling activity and intention of dementia patients and providing practical and contextual memory cues. We also put forward a guidance system to assist dementia patients. Finally, we would like to experimentally validate this earable-based guidance system in multiple ecological valid studies to uncover its efficacy in our work's future avenue.

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