Enabling remote assessment of cognitive behaviour through mobile experience sampling

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***Abstract*—Cognitive decline is among the normal processes of ageing, involving problems with memory, language, thinking and judgment, happening at different times and affecting people's live to a significant extent. Traditional clinical methods for cognitive assessment are conducted by experts once first symptoms appear. Mobile technologies can help supporting more immediate, continuous and ubiquitous measurements, thus potentially allowing for much earlier diagnosis of cognitive disorders. We present in this paper a digital mobile tool to administer cognitive tests in the form of multimedia experience sampling methods (ESM), which can run on a smartphone and can be scheduled and assessed remotely. The tool integrates digital cognitive ESM with passive sensor data that can be used to study the interplay of cognition and physical, social and emotional behaviours. We implement the Mini-Mental State Examination (MMSE) test, a clinical questionnaire extensively used to assess cognitive disorders, in order to showcase the possibilities offered by the proposed tool. Initial usability results show the tool to be perceived simple, easy and accessible for cognitively unimpaired persons.**

***Index Terms*—cognitive assessment, smartphone, mobile sensing, human behaviour, mHealth**

I. Introduction

According to the WHO, around one sixth of seniors suffer from a cognitive disorder [1]. The number of cases describing cognitive disorders increase at a yearly rate of 7.7 million. Cognitive disorders represent a malfunctioning of important abilities such as perception, attention, memory or language, which can interfere with daily life activities or independent function. As a consequence, cognitive disorders are becoming a worldwide threat to older adults' independence and quality of life.

Cognitive or mental operations involve processing information. Therefore, we can study how our mind works by studying how information is processed [2]. This is a practical principle used in several cognitive science methods, with the *Mini Mental State Examination* (MMSE) as the reference test in clinical practice. MMSE is a popular questionnaire-type test, extensively used in clinical and research settings, to diagnose cognitive disorders based on the observation of an individual's mental performance. The original MMSE, as defined by [3], consists of a number of sections including questions and problems addressing the time and place of the test, repeating lists of words, arithmetic operations, language use and comprehension, and basic motor skills.

The MMSE test starts with a temporal and spatial orientation task requiring the individual to correctly identify the current time (year, season, date, day, and month) and location (state, county, town, hospital, and floor). This section is followed by a *registration* task, where subjects are asked to repeat the name of three unrelated objects. Thereafter, *attention and calculation* are assessed by asking participants to subtract seven from hundred five times, or alternatively to spell the word "world" backwards. Subjects are then asked to *recall* the three objects introduced during the registration section. The final section covers *language* aspects, including multiple tasks that assess the subject's ability of *naming* (subjects are asked to name two given objects), *reading* (subjects are requested to read and follow a specific command), *writing* (subjects are asked to write a sentence of their choosing), and *copying* (subjects are requested to copy and draw two intersecting pentagons). The maximum achievable score is 30 points, but a score of 24 or higher indicates normal cognitive functioning [4], [5]. Below this, scores can indicate severe ($\leq$9 points), moderate (10–18 points) or mild (19–23 points) cognitive impairment [6].

Cognitive tests like the MMSE are typically conducted in the presence of a specialist. The role of the specialist, prior and during the test, normally limits to explaining the structure of the test to the participant and guiding them through the examination. The test answers are processed and assessed posteriorly. These tests require no specialized equipment or training for administration, thus making them ease to use [7]. However, the need for a person to introduce the test and collect the answers fairly constrains the frequency of administration of these tests. As a consequence, cognitive assessments are performed a few points in time and mostly upon clinical prescription when first symptoms appear. Moreover, the presence of an expert can affect the normal cognitive responses of the individual, hence introducing some level of bias in the results. In the light of these limitations, we propose a new approach to support the realisation of cognitive tests in an immediate, continuous and ubiquitous manner. The tool implements digital cognitive tests in the form of a multimedia experience sampling method (ESM), which can run on a smartphone and can be configured and scheduled remotely. The tool further integrates the digital cognitive experience sampling with multiple smartphone sensor data streams that can be used to study the interplay of cognition and physical, social and emotional behaviours. All the collected data is securely communicated via internet and made available to the expert through a server for its post-processing and analysis, while avoiding the need for the individual to visit the clinician's office or any dedicated facilities.

II. Related Work

Smartphone-based sensing has been explored in previous research to measure daily behaviours, which could in principle give insight into cognitive disorders. For example, various works have exploited the smartphone's inertial sensors, GPS and microphones for detecting indoor and outdoor physical activities [8], which may relate to the cognitive state of a person [9]. In a similar fashion, Bluetooth scans, photo captures and ambient audio recordings are used to measure levels of sociability [10], that may be associated to cognitive functioning [11]. Some sophisticated approaches even measure physiological parameters such as heart rate and breathing rate through the smartphone's accelerometer using ballistocardiography [12], which may be used to analyse cognitive stress [13]. The straight application of smartphones for the measurement of cognitive functioning is however a fairly uncharted area. There exist very few studies and they all mainly focus on the measurement of attention. In [14] the authors recorded mobile phone usage including messages, social media and internet navigation for fifteen users during approximately three months. The analysis of this data allowed them to identify potential fill or kill times or even breaks, normally related to boredom situations. Mobile phone interaction (e.g., amount and types of apps used), context (e.g., light levels) and demographics are also combined in [15] with machine learning techniques to automatically spot these boredom situations. The results of this work demonstrate that the recency of communication, usage intensity, time of day, and demographics are the best categories of features to fairly identify situations were attention is scarce. Smartphone-based assessments of alertness and fatigue are compared to the influence of chronotype and time-of-day performance in [16]. Measurements include questions on alertness, fatigue, as well as recent activities influencing levels of alertness and fatigue, such as the consumption of caffeine, exercising, or napping. This work shows that alertness can oscillate approximately 30% depending on time and circadian rhythms. The authors also concluded that daylight saving time, hours slept, and stimulant intake can influence alertness.

III. System description

Unobtrusive cognitive assessment based on mobile passive sensing requires to go hand-in-hand with the instrumentation of existing clinically-validated tests. In that vein, we propose MobileCogniTracker, a digital tool that complements and extends the potential of existing mobile passive sensing platforms for the measurement of people's cognitive functioning. MobileCogniTracker develops an innovative experience sampling tool to help automatising and objectifying the measurement of clinical-grade cognitive data. We describe next requirements, design choices and implementation of the proposed mobile cognitive tracking tool.

A. Requirements

We use the MoSCoW prioritization technique for the requirements elicitation. The tool must work on regular mobile devices. It must be possible to create different sections and tasks, typically organised around a specific cognitive ability, facilitating proper administration, reusabity and shareability among tests. The tool must facilitate the scheduling of tasks, allowing specialists to remotely specify when the test is presented to the user. In this way, the tests could be split into various parts, possibly measuring different cognitive abilities, which are administered at different times according to the study or user preferences. The data must be stored on a secure server for further analysis to avoid any malicious use by third unauthorised parties. The system must allow for extensibility, specifically for integration with new unobtrusive sensors and experience sampling modalities.

Answers to clinical cognitive tests are normally spoken. For other questions, users are asked to write or draw. Thus, different input methods should be supported. Voice input can be achieved through speech-to-text functionality, closely resembling traditional testing and further avoiding typing issues for users with motor impairment. It should also include a text-to-speech functionality, so that instructions are read-out-loud to the user to avoid misinterpretation and facilitate accessibility to people with mild visual impairment. It could be possible to shuffle test sections and tasks, thereby avoiding a learning effect on the subjects after executing the test several times.

B. Architecture

Figure 1 shows the high-level architecture of MobileCogniTracker. The mobile device is the core entity, enabling the communication between user and server. The specialist sets on the server the study properties, including the questions or tasks

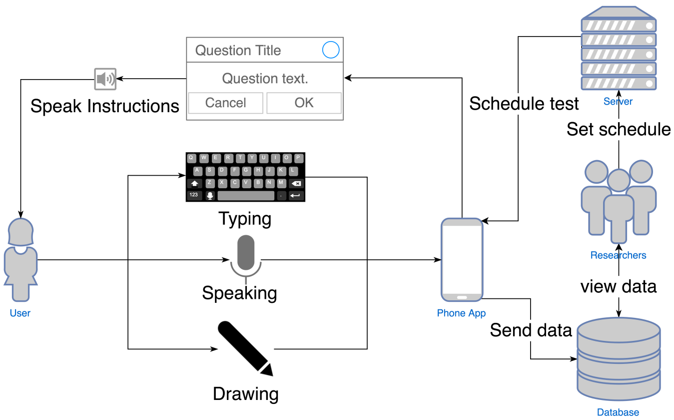


Figure 1: MobileCogniTracker architecture diagram

to be realised by the user and their schedule. The server communicates this information to the mobile application, which automatically updates the local configuration as to ensure proper operation in the absence of internet connection. At the scheduled time, the app pushes a notification awaiting for the reaction of the user. Once the user reacts to the notification, the corresponding cognitive test, i.e. question(s) or task(s), are prompted for its realisation. Questions and tasks can be read on the screen or spoken out for the user convenience. The user's answers, which can come in different modalities, namely text, voice and drawings, are stored temporarily on the mobile device. This, and conveniently other mobile sensor data, is sync periodically with the server as to make it available to the expert for performing the assessment.

C. Cognitive ESM

This section presents some examples of the cognitive mobile ESM developed in view of the aforementioned requirements. Text and numerical (Figure 2a) inputs are considered for answering questions such as those asking for the current date or location. These types of input are commonly used in mobile devices and they can be easily adapted to each user, e.g. by enlarging the font or display size through magnification. Some cognitive tests require copying given objects or sketching concepts (Figure 2b), which in turn involve to draw. Fairly ample canvases are considered for such drawings, which allow individuals to use their fingertips as a sort of pen. Some tasks involve the repetition of a given piece of text (Figure 2c). The voice is then used as input, which in combination with the text-to-speech functionality helps to automatically transcribe the answer of the user. This approach makes it possible to capture, in the form of text, any voice from supported languages, and virtually the automatic translation to any others. We also consider the development of an ESM to realise n-step command type tasks. These commands tend to involve manual handling, such as taking a sheet of paper in the right hand, fold it in half and place it on the floor, which poses special challenges to be implemented on mobile devices. The relevance of this task is not on the physical aspect but on remembering three different instructions and executing them. Users are presented first with the instructions, e.g. arranging some circles in a specific order depending on their colour, which are followed by the interaction space where the user can perform the task (Figure 2d).

D. Implementation

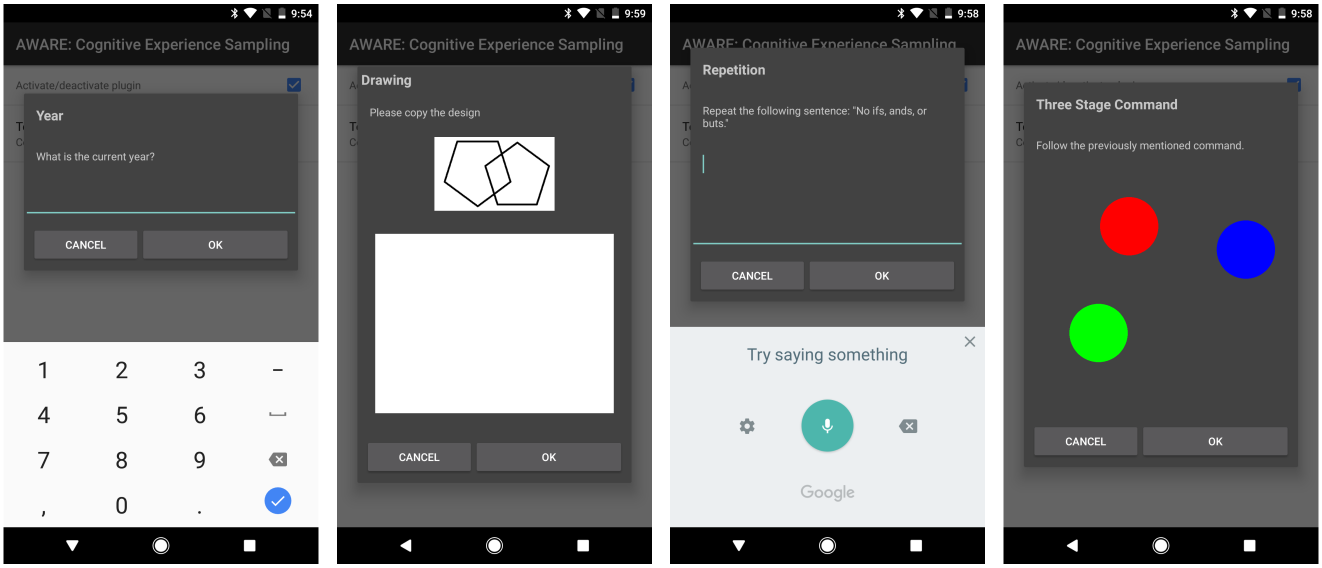
MobileCogniTracker has been developed using Android Studio Version 2.3, and it has been tested on Android versions 6.0-6.0.1 (*Marshmallow*), 7.0-7.1.2 (*Nougat*) and 8.0 (*Oreo*). The tool largely builds on AWARE (version 4.0.700.selfie), an Android-based open-source mobile instrumentation framework [17]. The motivation for choosing this framework is twofold: (1) it provides a client-server mobile framework that supports the collection of unobtrusive passive sensor data; and (2) it is licensed under the Apache Software License 2.0 so it allows for changes and extensions to the core code. For serialisation of XML files the Simple-XML serialisation framework for Java version 2.7.1 has been used.

The tool uses a server-client approach, which is enabled through AWARE. Experts can easily set up a study on the AWARE server through a web-based dashboard. Here, for example, the specialist can define the type of passive mobile data to be recorded on the user device, e.g., acceleration, battery usage or phone call logs to name a few. Users can then join a study by simply scanning a QR code through the AWARE mobile app. Once it is running, the app sends periodically the collected data to the server over WiFi or 3G. More information is available here [17].

AWARE also supports basic ESM, namely free text, radio buttons, checkbox, Likert scale, quick answer, scale, and numeric types. These ESM questionnaires are executed remotely and can be scheduled using the web dashboard or from within a plugin. It is possible to specify for how long the notification should be active for and how much time the user has to answer the question. The implementation of MobileCogniTracker thus consists of changes to the AWARE core and the development of a new Cognitive ESM plugin. MobileCogniTracker extends AWARE as to support the scheduling and construction of ESM-based tests provided in XML form. MobileCogniTracker can create an AWARE ESM questionnaire and set a schedule based on a definition in an XML file that follows the XML schema. A simplified example of the schema is given in Listing 1. This example shows the XML file for the MMSE repetition task, including, for example, the text-to-speech functionality to read the instructions out, speech-to-text to transcribe the spoken answer or the time for task administration set to *Sundays* at *12:30*.

Listing 1: This example shows the digitised repetition section of the MMSE.

```
<?xml version="1.0" encoding="utf-8"?>
<TestDefinition xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:noNamespaceSchemaLocation="TestDefinition.xsd">
<name>Mini-mental state examination Repetition Component</name>
<short_name>MMSE_REP</short_name>
<description>Participants are asked to repeat a sentence</description>
```



(a) (b) (c) (d)

Figure 2: Some examples of the developed cognitive ESM dialogs. (a) Orientation to time task with numeric input. (b) Repetition task with image-based instructions and drawing input. (c) Language task with voice input using text-to-speech functionality. (d) N-step command task with movable objects input.

```
<text2speech>true</text2speech>
<speech2text>true</speech2text>
<Component>
<name>Repetition</name>
<task>
<Question>Repeat the following sentence: —No ifs , ands , or
    buts.—</Question>
<Aware>
<ESM_Type>ESM_Freetext</ESM_Type>
<Title>Repetition</Title>
<Instructions>Repeat the following sentence: —No ifs , ands ,
    or buts.—</Instructions>
</Aware>
</task>
</Component>
<Schedule>
<id>SundayAfternoon</id>
<hour>12</hour>
<minute>30</minute>
<weekday>Sunday</weekday>
</Schedule>
</TestDefinition>
```

The responses to the cognitive ESM are stored in a central SQL database. The database contains among others: the device id which unequivocally and anonymously identifies each user, the esm field which shows the fired question/task or the user answer. For non-text-based answers, such as drawing, copying, and rearranging circles, the data is first converted to strings.

IV. Evaluation

A. Study setup

A usability study was conducted in order to evaluate how MobileCogniTracker is perceived by end-users. MobileCogniTracker is eminently targeted at older adults, which are more prone to develop cognitive impairment. Thus, a major part of the recruited participants were over the age of 55. However, the tool should ideally support the tracking of cognitive functioning irrespective of age. Hence, younger individuals were also consider for this evaluation. A total of 26 individuals were recruited of which 16 were male and 10 female. Subjects reported to have no cognitive impairment to their knowledge. A preliminary cognitive screening was out of the scope of this first evaluation. The study was conducted at the University of Twente (Netherlands). Informed consent was obtained from all participants for the publication of this case report.

Participants were arbitrarily provided with a smartphone, either Google Pixel, Samsung Galaxy S7, LG G5 or Huawei P9, which are relatively similar in size and functionality. MobileCogniTracker was installed on the smartphones beforehand. An instance of the MMSE was particularly considered for this evaluation as it implements most of the developed ESM. The test was scheduled at a given point in time and automatically communicated to the participant through a notification. Participants were instructed to click on the smartphone notification to start the test. The mobile phone would then open the first dialog box with the first section of the digitised MMSE. After completing the tasks of a given section, the user is automatically prompted to the next one, similar to the way it is performed for the MMSE pencil-and-paper format. The usability test was performed in a single day.

B. Methods

We use the System Usability Scale (SUS) [20], a ten-item questionnaire used to evaluate a system's usability. The SUS questions are as follows:

1) I think that I would like to use this system frequently.
2) I found the system unnecessarily complex.
3) I thought the system was easy to use.

4) I think that I would need the support of a technical person to be able to use this system.
5) I found the various functions in this system were well integrated.
6) I thought there was too much inconsistency in this system.
7) I would imagine that most people would learn to use this system very quickly.
8) I found the system very cumbersome to use.
9) I felt very confident using the system.
10) I needed to learn a lot of things before I could get going with this system.

The test results from the questionnaire were evaluated using the statistical software SPSS version 24. The data was tested for normality through the Shaphiro-Wilk test [22].

C. Results

The responses given to the SUS questions are marginalised over all individuals and presented in Fig 3. The final scores of the SUS ranged between 25 and 97.5, with a mean score of 71.25 (above 68, which is defined as the average [19]) and a standard deviation of 17. The Shapiro-Wilk test for the 26 test scores reported a significance of 0.363, therefore at a significance level of $\alpha = 0.05$ ($\alpha < 0.363$) the null hypothesis is accepted and normal distribution of the SUS scores can be assumed.

In addition to the SUS, participants were asked about their smartphone use and additional usability aspects. Half of the respondents reported using their smartphones every day for many different functions, whereas less than a fifth reported that they do not own a smartphone. When analysing the relation between the SUS scores and other variables such as age, education, or reported smartphone use no statically significant relationship could be found. The usability test showed that around 40% of the respondents would be willing to use the application on a weekly or daily basis, and more than 80% of the participants would be willing to use the tool in general. Users experienced the amount of questions asked in the digitised version of the MMSE to be right.

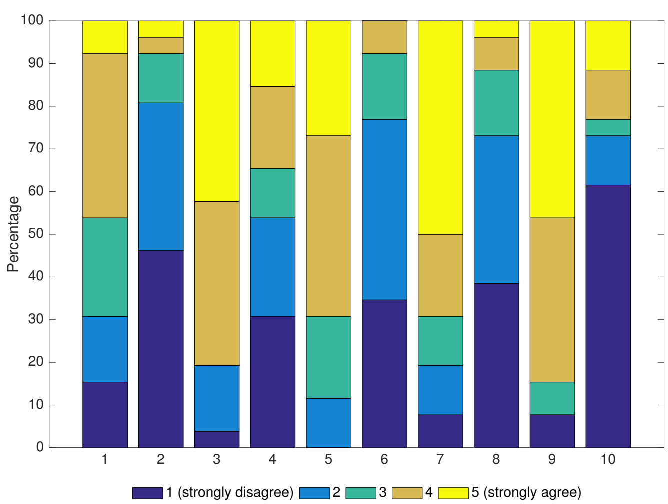


Figure 3: Distribution of the answers to the SUS marginalised over all participants. Each bar shows the results for each of the ten SUS questions. Each colour represents the type of answer.

V. Discussion

The usability evaluation showed in general a good level of satisfaction on most aspects. A majority of users reported MobileCogniTracker to be simple to use, easy to learn and coherent. A few participants would use the help of a technical person to initiate the tests. This has mainly to do with the fact that some people were either not familiarised with Android phones (i.e., iPhone users) or newer versions of the operating system. In those few cases, users were assisted beforehand as to be able to realise the test.

Participants also found the different ESM to be well integrated and straight forward to use. However, some users experienced some difficulties during drawing an copying tasks. These tasks have been tested using the finger as input, whereas in the original clinical questionnaires they are performed using a pencil. The results from the evaluation test showed that it is sometimes difficult, even for non-impaired subjects, to achieve precise results. Therefore, a stylus should be used as the preferred input method for this task, whether available. On a similar note, the use of tablets or phablets could facilitate the realisation of drawing tasks. Although users did not experience difficulties while using the provided smartphones, which are of a generous yet standard size, they anticipated potential difficulties while using MobileCogniTracker on smaller devices.

Participants perceived the amount of questions to be fair enough. MobileCogniTracker is intended for long-term monitoring, and as such, the frequency with which questions and tasks are administered plays an important role in the acceptance and engagement with the tool. However, such frequency fairly depends on how rapidly the cognitive ability may vary as well as the prominence of the task. MobileCogniTracker facilitates the scheduling of questions and tasks, which can be planned separately and spread over the course of a day, week and/or month. User preferences could be combined with requirements posed by the clinical tests as to maximise the effiency of the test. Hence, some questionnaires or tasks could be triggered once the user is available or test be shortened so that users can answer in a minimally-interruptive manner.

During the evaluation some participants mentioned that they perceived the questions of the MMSE as “too easy” and expected more challenging questions to measure cognitive performance. Users may thus required to be challenged according to their specific age and cognitive state, so personalised testing may result in a more enjoyable and engaging experience. MobileCogniTracker was not aimed at replacing existing clinically-validated cognitive procedures but to enable them digitally in order to facilitate their continuous, opportunistic and ubiquitous administration. This, however, opens up an interesting research area building at the intersection of cognitive assessment, personalisation and context-awareness, on which tests and contents are not simply digitalised but also tailored to preferences or life-events relevant to each individual.

The results of the usability study show that the tool is indeed usable by healthy subjects, even if they are not very familiar with the use of smartphones. The evaluation thus shows its potential use for tracking at least very early cognitive impairment, especially when starting with non-impaired subjects. It is unclear though how much cognitive impairment will influence the perceived usability of the application, and how much the application is capable to indicate the performance differences between cognitively impaired and non-impaired subjects. Future work should perform a more thorough evaluation considering screened cognitive impaired and non-impaired users, also comparing MobileCogniTracker to the paper-and-pencil version of cognitive assessment tests such as the MMSE. In this regard, the effect of external daily stimuli, the difficulty in translation from in-person to smartphone based assessments, and the difficulty for patients to use the technology should be fairly explored.

VI. Conclusion

This paper describes MobileCogniTracker, a mobile experience sampling tool that allows for the creation, administration and remote execution of digitised cognitive assessment tests. The tool provides multiple means to realise, on a user's regular mobile device, typical questions and tasks used in clinical practice to assess cognitive functioning. Several input types are supported for the realisation of the tests, including plain text, text-to-speech, speech-to-text and free drawing. As for standard experience sampling methods, MobileCogniTracker allows the specialist to schedule the time when a test should be administered. The specialist can also configure whether the test sections should be executed consecutively or at different times.

A preliminary usability evaluation has been performed in order to determine how users perceive the proposed tool. To that end, a digital implementation of the popular MMSE clinical test has been particularly considered. Results show that users are generally satisfied with the tool, which they find simple and easy to use. Tasks involving drawing on the screen can nevertheless be enhanced by using more accurate means than the fingertip. The performed evaluation is limited to healthy people with no recognised cognitive disorder. Hence, future work includes a longitudinal validation with cognitively impaired and non-impaired people as to ascertain the extent to which the tool is usable and accurate, especially in those cases with severe cognitive disorders.

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