Measuring cognition in population-based cohort studies

CLS working paper number 2021/5

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This paper was written in June 2019, and published as a working paper in March 2021 by the UCL Centre for Longitudinal Studies.

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How to cite this paper

Vasilichi, A.. (2021) *Measuring cognition in population-based cohort studies*. CLS Working Paper 2021/5. London: UCL Centre for Longitudinal Studies.

Contents

List of tables

Summary

- Cognition represents the mental processes supporting acquisition, storage, manipulation, and retrieval of information and how that information subsequently guides behaviour.

- Continuous development and increasingly widespread use of technology across all ages facilitates administration of cognitive tests in population-based studies, enable novel ecological data streams to be collected longitudinally, unobtrusively, passively, and objectively; this provides enriched cognition, behavioural, and physiological datasets, enabling novel and timely research to be generated across these domains.

- Novel technologies harnessed for enriched datasets on cognition comprise mobile (smartphone and tablet) applications, web-based cognitive testing, wearable technology, smart home systems, and non-invasive neural interface technology.

- Information on novel methods and measures used for cognition is provided (Appendix tables), along with information on the latest version of more traditional methods, and useful resources, relevant journals, wearable technology, and information on relevant companies and databases.

Aims

This scoping review has been conducted with the aim of finding opportunities for the longitudinal data on human cognition collected from the cohorts at the Centre of Longitudinal Studies UCL to be enhanced by:

1) novel data collection tools e.g. wearables, data from smartphones;

2) novel linkages e.g. consumer data, employer-held data, social media data; and

3) any other methods or measures with scientific utility.

Defining Cognition

Scientific research on cognition investigates the mental processes supporting information input and storage and how that information subsequently guides behaviour (Chamberlain et al., 2011; Wild, Nichols, Battista, Stojanoski, & Owen, 2018). These mental processes relate to the acquisition, storage, manipulation, and retrieval of information. Essentially, cognition represents the ability to perceive and react, process and understand, store and retrieve information, make decisions and generate appropriate responses. Furthermore, cognition can change and adapt to new information across our lifespan, regulating our behaviour during daily activities, in health and disease, and is a product of both our genetic makeup and environment.

1. Domains of Cognition

Research has revealed that cognition is not a unitary construct, but is rather constituted of several cognitive domains or functions, dependent on particular brain circuits, that underpin specific behaviours or actions (Hampshire, Highfield, Parkin, & Owen, 2012). In an attempt to measure these cognitive domains, computerized cognitive testing has been developed and validated to tap into particular brain regions, with many advantages over the traditional "pen-and-paper" methods, which will be discussed later. These domains are generally represented by attention, psychomotor ability, memory, executive function, and social cognition.

- Attention represents the ability to selectively attend to specific information or stimuli whilst ignoring irrelevant ones. Subdomains of attention are (visual) sustained attention measured by continuous performance on a task and selective attention measured by our ability to selectively attend to information.
- Psychomotor ability represents the relationship between cognitive functions and physical movements. Psychomotor speed is measured by an individual's ability to detect and respond to rapid changes in the environment (e.g. presence of a

stimulus). This measure enables assessment of reaction time, movement time and vigilance.

- Memory represents the ability to store information, short- or long-term. There are several subdomains to memory. Episodic memory is the ability to associate an event with a place and time. Recognition memory is the ability to recognise object, visual or spatial information. Working memory is the ability to hold and manipulate information in our mind, the mental space where we solve problems.
- Executive function comprises high-level thinking and decision-making. There are several subdomains to executive function. Mental flexibility is the ability to adapt thinking and behavioural responses. Planning is the ability to perform strategic problem solving or selection of appropriate action to achieve a desired goal. Strategy is the ability to implement strategic thinking while solving problems. Response inhibition is the ability to concentrate on relevant information to make appropriate responses, supressing responses to distracting information or interference.
- Social cognition is a growing field of research looking at how we process affective information and is assessed by responses to emotion-laden stimuli. Subdomains of social cognition are emotion recognition which is the ability to identify emotions in facial expressions and emotional bias represented by information processing biases for positive/negative stimuli.

Review of Methods Used to Measure Cognition

The tables in the appendix cover information on novel methods and measures used for cognition. There is also information on the latest version of more traditional methods. Additionally, the tables cover useful resources, relevant journals, wearable technology, and information on relevant companies and databases.

1. Traditional Methods

Implementing comprehensive batteries of cognitive tests in large population-based studies remains challenging considering their administration time and other resource constraints. Therefore, large scale longitudinal studies have relied more on utilising short and easy-to-administer cognitive tests, mainly using computer-assisted personal interviewing (CAPI), whereas running smaller-scale studies has provided greater feasibility to administer more comprehensive assessment batteries (Moulton et al., 2019).

2. Innovative Technologies for the Assessment of Cognition

Given the continuous development and increasingly widespread use of technology, there is growing potential for it to be utilised in large scale and longitudinal studies to assess cognition in adults. The Office for National Statistics reported that in 2018, 90% of UK households had internet access and 78% of adults were using mobile phones to use it, making it the most popular method for accessing the internet (Prescott, 2018). New technology is also rapidly adopted by older generations, as a constant increase in the Internet and smartphone use in the last years illustrates (Centraal Bureau Statistiek, 2016). An exception is the over 65's who preferred tablet computers, but nonetheless favoured mobile phones to access internet on the go (Prescott, 2018). This may indicate that for assessing cognition it may be best to choose a method that has applications for tablets, phones, and desktops.

There have been a few reviews outlining the different methods available for assessing cognition using novel digital technologies. Perhaps the most extensive is a clinical review conducted by Chinner, Blane, Lancaster, Hinds and Koychev (2018) who reviewed the digital technologies available for the assessment of cognition. This review summarises currently available evidence on digital technologies that can be used to assess and monitor cognition and those that monitor broader indices of activity and function. These have been used to assess and assist elderly demented, prodromal and preclinical populations. Most technologies covered in their review were targeting the measurement of cognition in older adults. Nonetheless, these technologies could potentially be harnessed for use in younger populations, especially those based on conventional neuropsychological tests where established age-related performance norms are available for comparison (e.g., the iVitality smartphone-based app, e.g. Jongstra et al., 2017). They categorised digital systems into 3 groups: i) mobile (smartphone and tablet) applications; ii) wearable technology; and, iii) smart home systems. Previous research on cognition has also relied upon iv) web based administration of cognitive testing (Hampshire et al., 2012). The studies included in the review of Chinner et al. (2017) reported good level of agreement between the digital measures and constructs measured. However, most technologies for measuring cognition are still in the initial stages of development.

i. Mobile (Smartphone and Tablet) Applications

There are novel opportunities for data collection from the widespread use of smartphones (including among the older generations) with a range of built-in sensors, good storage and battery capacities, possibility of real-time data collection, built-in internet connectivity, location services, and fast processors (Intille, Lester, Sallis, & Duncan, 2012). Their storage and connectivity capacities would enable collecting and sending large amounts of data. The use of activity monitors may influence participants to change their behaviour (Trost, Mciver, & Pate, 2015), but passive collection of data with smartphones may reduce this effect.

Smartphone technology has already enabled remote monitoring of health parameters, i.e., physical activity and blood pressure, which have been widely studied and found feasible in older populations too (Wijsman, Richard, Cachucho, de Craen, Jongstra, & Mooijaart, 2016; Fong et al., 2016). Smartphone-assisted cognitive testing would enable assessment of cognitive functioning rapidly and repeatedly in a non-invasive manner, at a convenient time for participants, being cost-effective and having low participant burden.

Studies testing the use of smartphone for standardized cognitive assessment in everyday environments pave the way to integrate this method in a home setting (Timmers et al., 2014). Timmers et al. (2014) had young adults complete a short-term memory task in either an everyday-life environment or a controlled test setting at four time points during a day. There was no significant difference in task performance between the two conditions ($F(1, 24) = 0.28$, $p > .60$). Furthermore, the correlations between fatigue, tension, or environmental noise and task performance were not significant at the time of testing, meaning task performance is not affected by these factors. There were also statistically significant correlations between task performance at subsequent time points during the day in the everyday-life environment, suggesting high test-retest reliability and commitment of the participants. Thus, smartphones can be utilised to reliably assess cognitive functions outside a laboratory setting, in the participant's own natural habitat.

Previous research described the feasibility and validity of smartphone-based cognitive testing, however focused on specific patient groups or a specific cognitive test (Brouillette et al., 2013; Tieges et al., 2015; Bajaj et al., 2015). Furthermore, little is known about the feasibility and validity of applying multiple cognitive tests using smartphones for clinical research in larger populations (Jongstra et al., 2017). Cognitive assessment with an app is only feasible under conditions where participants comply (Giordano et al., 2016) and of optimal technical performance (Jelcic et al., 2014). Jongstra et al. (2017) evaluated the feasibility and validity of performing cognitive tests in 151 healthy adults using smartphone-based technology during a 6 months follow-up period. They developed five digital versions of cognitive tests for the iVitality smartphone app based on existing neuropsychological tests, adapting them for smartphone use. Every two weeks participants completed each test four times at different time points of day. The iVitality smartphone app prompts users to complete tests, collects the test results, shows them to the user, and transfers the data to the iVitality website and database. Results showed moderate correlation between the smartphone-based test and the conventional test for the Stroop test (testing selective attention) and the Trail Making test (measuring attention and executive function) with Spearman ρ=.3-.5 (p <.001). Thus, smartphone-based cognitive testing potentially provide the opportunity for large-scale longitudinal data-collection in population studies and repeated monitoring of cognitive functions at home.

Frequent, brief and repeated self-administered mobile cognitive assessments in daily life settings represent a promising complementary tool to traditional methods of cognitive assessment (Moore, Swendsen, & Depp, 2017). Although the widespread use of smartphones enables app based cognitive assessment, the research has only begun to explore the utility of mobile cognitive assessments (Moore et al., 2017). Moore et al. (2017) conducted a comprehensive review and identified 12 articles utilising self-administered smartphone-based cognitive assessments. Samples tested were healthy individuals between 14 to 83 years old. The most frequently assessed cognitive domains were working memory (7 studies) and attention/reaction time (4 studies), with mean adherence rate of 79.2% reported in 7 studies. Results showed support for high levels of between- and within-person reliability and construct validity. Thus, smartphone-based cognitive assessment is a promising complementary tool to traditional assessment, has the potential to enhance capacity to inform individual-level outcomes over time (i.e. changes in cognitive performance) and assess cognition and the factors it correlates with in the naturalistic environment.

As cognitive assessment moves onto personal computers and mobiles devices, engagement is important to collecting high-quality data. In recent years, a large number of cognitive tests have been gamified, that is, game design features have been incorporated into cognitive tasks without undermining their scientific worth. The purpose is improving data quality and participant engagement. In a systematic review, Lumsden, Edwards, Lawrence, Coyle and Munafo (2016) found several gamified cognitive tasks across various domains, working memory and executive functions being most common domains targeted for gamified assessment. Also, gamified tests were generally validated successfully. On average, the review found no evidence that gamified tests improve data quality, some studies indicating it may worsen it. However, the studies reviewed utilised small sample sizes and heterogenous study designs which means further research into gamified testing needs to be conducted. Nonetheless, gamified testing validated against more traditional measures focused on measuring single domains, provides engaging and scientifically valid cognitive assessments, making participants experience less effort and potentially reducing drop-out rates in longitudinal studies.

Mobile-based apps could benefit from enriched cognition datasets if they focus on participants engagement and enjoyment. Thirkettle, Lewis, Langdridge, Darren and Pike (2018) developed and assessed the utility of 1-2-minute versions of classic and novel cognitive tasks embedded in a mobile phone and tablet app. The app was designed to encourage repeated play and focused on participants as users. OU Brainwave app collected a rich dataset from around 14,000 active participants in multiple, self-paced, sessions of classic working memory (N-back), sustained attentional focus (Persistent Vigilance task), spatial cognition (Mental rotation), and split attention (Multiple object tracking) tasks, and an implementation of a comparatively novel action learning task. The app also measured time-of-day variation in cognitive performance. Data was collected along 18 months. The app prompted reengagement at set intervals, however participants freely chose the number of times they wished to repeat the tasks. Results showed that very short testing periods along with allowing participants to choose their own levels of engagement, i.e., which tasks they want to play and how many times, produced a substantial and reach dataset. This approach introduced increased variability in the performance data making it challenging for data analysis. However, having replicated expected results and the app being sensitive to group level differences in performance, suggests that research apps testing cognition that focus on user engagement and enjoyment produce valid and reach datasets.

Utilising mobile platforms enables new data streams to be leveraged (Dahmen et al., 2017; Müller, Preische, Heymann, Elbing, & Laske, 2017) which can be collected largely unobtrusively, passively, and objectively with mobile platforms, reducing user burden and increasing ecological validity (Koo & Vazir, 2019). Such data can be timing data from cognitive assessments (Müller et al., 2017), timing data and performance measures from games (Tong, Chignell, Tierney, & Lee, 2016), sensor data from GPS (Tung et al., 2014), virtual reality performance data (Ip et al., 2017), and changes in speech (Konig et al., 2018) or changes in movement (Suzumura et al., 2018), data from mobile sensors, keyboard interactions, and data obtained from everyday use of social media, wearables, and mobile devices (Jain, Powers, Hawkins, & Brownstein, 2015; Insel, 2017). Utilising these new data streams provides a description of a person’s behaviour, i.e., “digital phenotype” (Wiederhold, 2016).

There is also an increased demand in assessing human physiology and cognition in more ecological ways as people go about their life, and/or when particular events occur. Thus, mobile-based cognitive assessments and these novel data streams enable contextual cognition data to be collected and correlated with physiological data, and data about the participant's environment. This is further enabled by remote assessments with mobile technology which are ideal for ambulatory assessments (Timmers et al., 2014; Lange & Suss, 2014) and ecological momentary assessments (Kleiman et al., 2017). This enables participants to take tests at a preferred time in a comfortable environment (Rentz et al., 2016) and to complete cognitive assessments several times a day (Allard et al., 2014; Jongstra et al., 2017). Researchers are thus enabled to generate and investigate novel and comprehensive research questions on the complex interaction between context and cognition (Allard et al., 2014).

ii. Web-based

In recent years there has been a rise in computer-based batteries to assess cognition for both researchers in academia and healthcare practitioners. Some of these were developed based on long-standing empirically sound neurocognitive measures, have been validated by researcher groups not involved in their commercial development, have increased focus on ecological validity, and utilise remote data storage and automated syncing to databases (Koo & Vizer, 2019). Computerised cognitive batteries are particularly useful when research requires testing large populations longitudinally (Owen et al., 2010). They are easy to administer and collect data with, they capture millisecond timing accuracy, enable randomized presentation of stimuli over multiple trials and administrations, and overall, they are unobtrusively measuring cognition and response times throughout the entire assessment process. Computerised cognitive batteries are also able to read the raw data and process it to generate summary statistics for each participant. Finally, administration of computerised tests is standardised and unaffected by examiner bias and can even be administered by examiners with limited training.

Empirical evidence about the comparability of computerized cognitive batteries with mobile cognitive assessment was provided by Mielke et al. (2015) who compared performance of 331 individuals aged 50-97 years old on the personal computer (PC) and iPad versions of the CogState battery. The CogState PC battery consisted of a detection task, one card learning task, identification task, one back task, and the Groton Maze Learning Test. Since the PC CogState battery is digital, the same questions were administered via iPad, but with different ways of interacting: keyboard and mouse for PC, and touchscreen and stylus for iPad. The PC and iPad versions of CogState were completed with a 2-3 minutes break in between. Compared with the iPad (M = 0.774s), individuals performed faster on the PC (M = 0.620s; $t = -21.27$, $p < .001$). They were also slightly more accurate on the one card learning task (visual recognition learning task) for the PC (M = 1.057 for PC versus M = 1.028 for iPad, $t = -5.47$, $p < .001$). Although significant, the differences, however, were small. However, participants preferred the iPad to the PC and thought they did better on the iPad. Thus, performance on cognitive functions tests on mobile technologies is similar to web-based performance.

Data quality represents an important issue for performance on cognitive measures. Having participants remotely complete cognitive measures online compared to bringing them in the lab or having examiners deliver these measures in participants homes, confer several benefits especially when testing cognition in population-based studies longitudinally. Thus, an important question is whether data quality on cognitive measures is comparable in the two cases. Germine et al. (2012) compared performance on cognitive tests performed on the web and those performed in the lab. It was commonly believed that data from self-selected Web samples comes with a trade-off between having a large number of participants and data quality. Concerns are pronounced about data quality for performance-based cognitive measures, particularly when timed or involve complex stimuli. Germine et al. (2012) took data from three different batteries of tests that have been described and validated in peer-reviewed studies, having good psychometric properties. These included tests of visual memory (Abstract Art Memory Test), verbal episodic memory (Verbal Paired Associated Memory), and working memory (Forward Digit Span). Results showed there was no systematic difference between web samples and those obtained from traditionally recruited and/or lab-tested on three key performance metrics, mean performance, performance variance, and internal reliability. Thus, completing measures of cognition on the web independently (i.e., without the supervision of a researcher) yields comparable results to when completing measures of cognition in the lab and/or supervised by a researcher.

One benchmarked web based neurocognitive assessment tool is Cambridge Brain Sciences (CBS) whose tasks have been used in more than 300 peer-reviewed studies over the past 25 years. In addition to the usual benefits of computerised or mobile cognitive assessments, CBS consists of highly engaging 12 cognitive tests which facilitate more completions and fewer study dropouts, therefore better participant compliance. These tests assess a broad range of cognitive abilities that can be categorized into three cognitive domains: reasoning skills, short-term memory, and verbal processing. This battery has been widely validated and previously used in large cohort studies which makes it a good option for large cohorts longitudinal studies.

This cognitive battery demonstrates scientific utility having been used in previous large (including longitudinal) studies to investigate whether widely believed theories are supported by scientific evidence. For instance, Owen et al. (2010) sought to provide scientific evidence for the claim that regular use of computerised tests improves cognitive functioning. They had 11,430 participants averaging 40 years old train several times each week for six-weeks on online cognitive tasks designed to improve cognition. Participants were randomly allocated to either a focused group training on six reasoning, planning, and problem-solving tasks; a ‘general cognitive training’ group training on six tests of memory, attention, visuospatial processing and mathematical calculations (similar to those in commercial brain-training programmes); or a control group who completed general knowledge questions. All three groups completed benchmarking assessments before and after the training, completing four tests adapted from CBS measuring reasoning, verbal short-term memory, spatial working memory and paired-associates learning. Outcome measures was the difference in the four benchmarking scores in the three conditions, representing the generalized cognitive improvement from training. Results indicated that both experimental groups improved numerically on three-four benchmarking tests with effect sizes from small to very small. However, the control group also improved numerically on all tests having similar effect sizes. Improvements were also observed in every cognitive task trained. Overall, this provided no evidence for generalized improvements in cognitive function from cognitive training in a large sample of healthy adults.

This cognitive battery has also helped clarify there are distinct cognitive domains to be tested when measuring cognition. Measuring cognition longitudinally in population-based studies is time consuming, therefore some studies gave preference to tests measuring variables believed to be unitary such as intelligence (Moulton et al., 2019). However, is human intelligence a unitary component or is it comprised of several distinct cognitive components? Thus, Hampshire et al. (2012) investigated whether intelligence is composed of multiple independent cognitive components processed by functionally distinct brain networks. A common set of frontal and parietal brain regions support a broad range of tasks that load on general intelligence. These areas are referred to as multiple demand (MD) regions. Hampshire et al. (2012) factor analysed regional brain activation levels while participants performed 12 CBS cognitive tasks in the MRI scanner. Then, they identified how many functionally distinct networks were apparent in the MD cortex while completing those 12 distinct cognitive tasks. Then, they compared factors obtained from the brain with factor models of individual differences in cognitive performance (i.e., behavioural data) in a large population sample (n = 44,600). They looked at whether the same set of cognitive components visible in the functional organization of the brain are visible in individual differences in cognitive performance. Results showed intelligence is not unitary, but emerges from anatomically distinct cognitive systems, each being responsible for specific cognitive components. This means that any viable attempt to measure cognition should utilise a set of cognitive measures which tap into these distinct cognitive components, thus providing a comprehensive description of an individual's personalised cognitive makeup.

iii. Wearable Technology

Current wearable technology consists of a variety of wearable devices, wearable sensors, electronic skin patches, electronic textiles (e-textiles or smart clothing; the introduction of electronic functionality into textile systems), augmented, virtual & mixed reality (AR, VR, MR), haptics (e.g., notification provision in a vibrating smartphone), user interfaces and more. Perhaps, the wearable technology currently most relevant to measuring and inferring cognition in adults is that commonly used by the Quantified Self movement.

a. Quantified Self

Within the Quantified Self (QS) movement currently leveraged in wellness and healthcare individuals collect data on themselves, tracking their own state and behavioural patterns (e.g., number of steps, heart rate, sleep patterns) using personal trackers such as Fitbit, Jawbone, iPhone, and similar devices (Fawcett, 2015). To do so, individuals utilise a wealth of digital data generated by wearables, applications, and self-reports enabling them to assess diverse domains of their daily life. These are personal devices used for continuous and mostly unobtrusive tracking. More specifically, domains tracked are physical states (e.g., mobility, steps), psychological states (e.g. mood), social interactions (e.g., number of Facebook "likes") and environmental context (Wac, 2018). Data and analysis on these four domains contribute to individual's quality of life.

b. Quantified Self Technologies

Self-tracking is enabled by the latest available personal wearable technologies and mobile applications. Wac (2018) conducted a database search of wearables available from Vandrico

Inc. (http://www.vandrico.com/; free and claims to provide up-to-date information about the latest technologies). The search identified 438 wearables between 2001-2016 and beyond. These were described by the sensors used (e.g., accelerometer), goal (i.e., phenomenon tracked), and the placement of the wearable on the body (e.g., wrist). Thus, gathering data on the self is enabled by ubiquitous availability of technologies adopted by personal computing and communication devices and services. Overall, these collect multiple types of high-resolution data (e.g., location, physical activity) longitudinally and unobtrusively. Many wearables are also paired with their web-based services, thus providing advanced analytics and visualization of data to its user.

Wac's (2018) search yielded the following results on three variables of wearable technology:

- Raw Sensor Data Acquisition: The raw sensor data acquisition embedded in the analysed wearable was mostly an accelerometer by far (i.e., motion detection sensor, tracks the basic human movements in all directions), followed by button-based interface, digital clock, gyroscope (i.e., device that detects orientation and rotation, can be used for navigation), heart rate monitor, GPS, touch interface, kinaesthetic interface (vibrator) or LCD-based display, with microphone and audio speaker.

- Behaviours Tracked/Enabled: The data acquired enable higher-level behaviours or behavioural aspects to be tracked. These are physical activity (far ahead), followed by phone notifications and phone controls, sleep, and geo-localization. Wearables can also enable behaviours or novel form of interactions with connected objects and communications. Additionally, some wearables can track behaviours such as eating, dreaming, urinary infections, and foot pressure.

- Positioning on the Body: Wearables were found to be most frequently positioned on the wrist by far, followed by head, torso, chest, ear or arm. The search also identified wearables that can be positioned anywhere on the body to track the required data.

Furthermore, results indicated that over the years wearables emerged to rely on accelerometers as integral part, physical activity becoming an integral behavioural variable being tracked. Along the way, phone notifications and controls appeared, being powered by advancements in short range communication such as Bluetooth that enables data exchange between a wearable and a phone. As indicated, wearables are most commonly positioned on the wrist, but advancements in miniaturisation enabled placement on the head, torso or anywhere.

c. Wearable Technologies and Cognition

A recent review reported several studies that evaluated digital technologies designed to monitor or assist cognitive function in older adults with dementia or from the preclinical population (Chinner et al., 2018). Generally, these studies deduced cognitive function through activities of daily living (ADLs) performance. Chinner et al. (2018) reported several studies utilising wearables (i.e., smartwatches, accelerometers, cameras and glasses) for elderly with objectives that could be divided into cognitive monitoring and assistance.

Thus, four smartwatches were identified which monitor physical and cognitive function by proxy in patients with dementia. WanderRep is a smartwatch reporting tool to be used by caregivers of wandering persons with dementia (Cachia, Attard, & Montebello, 2014). The tool records time, location, temperature and activity levels to create personalised profile of wondering risk, thus modelling patient's behaviour and alert caregivers when potentially dangerous events occur. Max (Netscher, 2016), u-Healthcare (Shin, Shin, & Shin, 2014), and Basis B1 (Boletsis, McCallum, & Landmark, 2015) use smartwatch-derived measures to create activity profiles of patients with dementia. Piloting Max in the homes of 13 healthy controls found that reported room detection accuracy was 91%, being able to detect distinct user behaviour patterns (Netscher, 2016). u-Healthcare was piloted in 8 participants with an average of 94.7% reported step detection accuracy (Shin et al., 2014). Thus, smartwatches monitoring can be utilised as complementary tools to monitor cognitive health and behaviour. Smartwatches have also been developed for preclinical populations. The wrist wearable unit (WWU) monitors longitudinally physical activity levels at home of preclinical older adults using measures of step count, acceleration and heart rate (Ahanathapillai, Amor, & James, 2015). Piloting WWU in groups of 2-20 healthy adults demonstrated to reliably determine preclinical function, thus identifying changes indicative of physical and cognitive decline (Ahanathapillai et al., 2015).

Moreover, one study utilised accelerometer data monitoring older adults' physical activity to infer cognitive status (Stubbs, Chen, Chang, Sun, & Ku, 2017). In a longitudinal study, 274 older community-dwelling adults waist-worn a triaxial accelerometer over 22 months. Light physical activity was associated with better cognitive function as measured by AD8 (including memory, orientation, judgment and ADLs).

Chinner et al. (2018) also identified three wearables which assist cognitive function in patients with dementia. Thorpe et al. (2016) investigated the potential of commercially available smartwatches to provide ADL assistance to patients with dementia. They implemented smartwatch apps paired with a smartphone to assist scheduling, navigation, orientation to time and communication, and monitor overall activity levels. Initial tests indicated scheduling, orientation and communication functions were usable (90-100% tasks completed using these functions, compared to 0% when using navigation and emergency help tasks). Furthermore, SenseCam is a wearable camera system supporting autobiographical memory consolidation and retrieval (Brown et al., 2011). This captures pictures every 30s in response to specific triggers which the patients review subsequently. A two-week test indicated cognitive impaired individuals improved ability to recall events from 38% at baseline to 68% day thirteen compared to using a diary (30%) which sustained at six months' follow-up. Moreover, smart glasses in the form of head-mounted display can assist patients to navigate around their homes (Firouzian, Asghar, Tervonen, Pulli, & Yamamoto, 2015). The system communicates with a remote android via Bluetooth. Then, caregivers can use the remote unit to monitor location and provide the patient with navigational cues through the glasses' LEDs.

iv. Smart Home Systems

Smart home technology has been used to provide assistance to people experiencing cognitive decline (Chinner et al., 2018). Although such systems have not been designed to directly monitor cognition, they have potential to infer and monitor cognitive function by observing changes in patients' activities of daily living. In such systems, technologies are built in the infrastructure of the building consisting of magnetic contact sensors, passive infrared motion sensors and pressure mats which are used to monitor the environment. Then machine learning algorithms are applied to the data to conceptualize patterns of behaviour and deviations to assess cognitive health. Subsequently, a decision-making system reacts to deviations, providing feedback to patients and caregivers.

Three studies were identified which assessed the accuracy of smart homes in detecting participants' performance while completing ADLs. Machine-to-Machine (M2M)/Internet of Things (IoT) system reported 80%-100% detection accuracy for most ADL activities (Ishii, Kimino, Aljehani, Ohe, & Inoue, 2016). DemaWare2 system reported 82% precision for recognising activities performed in the lab and 75% at home (Stavropoulos, Meditskos, & Kompatsiaris, 2017). The third system found a significant correlation (r = 0.54) between ADL performance scores from the caregiver and those from the system (Dawadi, Cook, Schmitter-Edgecombe, & Parsey, 2013). Overall, accuracy for determining user's performances varied depending on the type of activity assessed. These results are indicative that smart homes can monitor several ADLs to detect cognitive function and decline. These systems can do so unobtrusively to gather longitudinal data.

Furthermore, two smart homes were used to examine the capability of such systems to discriminate cognitive states and dementia status. DemaWare2 system was found to distinguish between the three participants groups in the study (including cognitively healthy participants) with up to 84% accuracy (Stavropoulos et al., 2017). A second study found machine learning methodology used by a smart home system was able to classify the cognitive health status of 263 participants (196 cognitive healthy and the remaining were experiencing cognitive decline; Dawadi et al., 2013). Thus, these systems can differentiate between cognitively healthy and dementia participants with reasonable accuracy. This demonstrates that monitoring ADL performance by smart homes is feasible and can infer cognitive states and cognitive decline over time.

v. Non-Invasive Neural Interface Technology

EEG (electroencephalography) and fNIRs (functional near-infrared spectroscopy) technology have been utilised both in research and the consumer market. EEG brain scans have been traditionally used over decades in the monitoring and diagnosis of patients with medical conditions such as epilepsy and sleep disorders (Thakor & tong, 2004), and in research measuring neural activity when participants complete cognitive tasks (Debener, Minow, Emkes, Gandras, & De Vos, 2012; Lin et al., 2014). fNIRs have become a sort of "mobile-MRI" (MRI – magnetic resonance imaging) capable of adding an extra stream of neural data in cognitive assessments (Harrison et al., 2014). These technologies are utilised in clinics, being used in various instances including epilepsy, sleep disorders, and traumatic brain injury. Novel applications continue to arise; in consumer goods, non-invasive biosensors can be integrated in easy-to-wear headsets for applications such as education and training, entertainment, health and wellbeing (Khushaba et al., 2013). Then, neural activity can be wirelessly tracked as participants complete cognitive tasks or activities in a variety of environments (e.g., school), and verify results on one's own phone (Debener et al., 2012). Thus, wireless EEG could provide an added dimension to cognitive assessments, some devices providing real-time analysis of EEG indexes of cognition, alertness and memory (Berka et al., 2014). Further research should be conducted to investigate the accessibility and quality of available wireless EEG devices, thus their potential to be a useful addition to the plethora of novel technological devices for cognitive assessment in large-scale longitudinal studies.

Conclusion

The research reviewed suggests that enriched cognition data in the participants' naturalistic environment can be harnessed through conducting cognitive assessment and monitoring with the use of smartphone-based, web-based, wearables and smart home systems devices. Gamified tests focused on user engagement and enjoyment further enrich and enlarge cognition datasets by increasing participants adherence. Utilising novel data streams from behavioural, physiological, and even neural measures enabled by use of novel technology (mobiles, wearables, smart home systems, non-invasive neural interface technology) further enriches datasets. This enables large-scale longitudinal studies to effectively use their enormous human datasets to generate novel and timely research on the complex interaction between environment, physiology and cognition.

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Table 1: Tests of Cognition for Adults

Products	Domain(s) Measured	Description	Administration	Link / Reference Table / Contact
Cambridge Brain Sciences	It assesses a broad range of cognitive abilities that can be categorized into three cognitive domains: → reasoning skills → short-term memory → verbal processing	Table The full assessment (12 cognitive tests) takes between 20-45 minutes. You can schedule a demo with them as well.	Web-based neurocognitive assessment tool	Table 2 in this document. Database with a lot of publications which have used this battery / these tasks: https://www.cambridgebrainsciences.com/science/research
Adaptive Cognitive Evaluation (ACE) Explorer	Basic Reaction Time Attention Working Memory Goal Management	"The adaptive algorithms allow each task to be completed in approximately 5 minutes and ensure that comparisons between individuals of different ages, genders, races, or cultures reflect actual differences in their cognitive ability and not disparities in the testing parameters or ceiling/floor effects. ACE can also be retaken any number of times to benchmark and track an individual's changing cognitive control abilities over time." The adaptive algorithms means that the same game can be used from ages 7 to 100 across the life span.	This is a Uniti App available on mobile and tablet devices for both Apple and Android. By using this battery, researchers would be able to perform cognitive assessments remotely. The App is currently being validated and it is foreseen that within the next 6 months – 1 year it will be benchmarked. Aspects of the App might be developed further, therefore you will have to get in touch with the development team if there is intention to utilise it.	Link to ACE Explorer website: https://sites.google.com/view/aceexplorer/home Table 3 in this document.
CANTAB Connect Research		Table 4 in this document.		Table 4 in this document.

NIH Toolbox Cognition Battery – Ages 18+		Table 5 in this document.	The measures can be administered with an iPad App. No internet access needed during administration. It automatically calculates normed and composite scores. Data is stored on the iPad and can be exported in multiple ways (e.g., send to iCloud, email data files)	Table 5 in this document. NIH Toolbox Support Center (very detailed information on everything): https://nihtoolbox.desk.com/
Cogstate Research™	Each test has been designed and validated to assess specific domains including psychomotor function, attention, memory, executive function, verbal learning and social-emotional cognition	Table 6 in this document.	Online platform; can be administered on a PC / iPad	Table 6 in this document. Information on the battery: https://www.cogstate.com/academic-research/ Database with a lot of publications which used this battery / these tasks https://www.cogstate.com/publication/
Sea Hero Quest	Spatial Cognition Human spatial navigation represents the ability to navigate through an environment.	Designed to investigate the brain's capacity for orientation/spatial awareness. Participants navigate their way through each level of the game. It gathers data on the average person's ability to navigate. Scientific data: "While playing, every 0.5 Seconds the game records the location and orientation of the boat in the game level currently played. This, combined with demographics information entered and the choices made in flare levels, provides the science team with the data to measure spatial navigation ability."	Mobile game designed to be played on a mobile or tablet device. Sea Hero Quest VR By using the App with Virtual Reality it is also possible to track eye movements	http://www.seaheroquest.com/site/en Frequently Asked Questions: http://www.seaheroquest.com/site/en/faq

Metacognition	Metacognitive sensitivity represents the ability to distinguish between accurate and inaccurate performance. It is a relatively stable ID and is related to generic resistance to recognising and revising incorrect beliefs.	Researchers from MetaLab at UCL (http://metacoglab.org/) are developing an app together with a London-based technology company DamnFire to quantify metacognition via a series of decision-making games: https://www.metacogmission.com/ The app is not available for general use yet. Nonetheless, Dr Steve Fleming consented to mention this App in this report as a prospective data collection method of metacognition and include his contact details to follow up.	Online App: https://www.metacogmission.com/ In its current state the app can be utilised on any device: desktop computer, tablet, smartphone. However, the App will be developed further, therefore you will have to get in the touch with the development team if there is intention to utilise it.	https://www.metacogmission.com/ Principal Investigator: Dr Steve Fleming stephen.fleming@ucl.ac.uk
LEAP-Questionnaire: Language Experience and Proficiency Questionnaire	Assessing language profiles in bilinguals and multilinguals.	Comprehensive measure	The questionnaire can be downloaded from the website I linked in the adjacent section. It is a word document with a comprehensive set of questions. This questionnaire can be administered online or offline.	https://bilingualism.northwestern.edu/leapq/
Mezurio	N/a	Used by researchers to deploy games to test cognition in their studies. Participants can complete interactive, scientific measurement tasks. It's designed to be used as part of a research study. Participants can contribute different kinds of data quickly, frequently, and from their own home. Example of study where it has been used: assessed long-term memory in adults at risk of Alzheimer's Disease https://www.biorxiv.org/content/10.1101/599175v1	Smartphone App for Android and iPhone mobile devices Remote administration	https://mezur.io/

mEMA (ecological momentary assessment)	Can be used by researchers using: Ecological Momentary Assessment (https://ilumivu.com/about/science/ecological-momentary-intervention/), Experience Sampling methods (https://ilumivu.com/about/science/experience-sampling/), Ambulatory Assessment (https://ilumivu.com/about/science/ambulatory-assessment-app/)	Collect real time-data from participants as they go about their daily life. It is possible to combine data from self-reports, phone sensors, and wearable sensors. It is possible to control which surveys and tests are presented to whom and when they see it. Context aware: capture location, ambient noise, light levels, weather etc. Capture Physiology: integrate with wearable sensors to capture Heart Rate, Heart Rate Variability, electrodermal activity (EDA), motion, galvanic skin response (GSR) and other biometrics.	Mobile App for both Apple and Android smartphones Remote administration	https://ilumivu.com/ *Scientific worth example:* "Examination of Real-Time Fluctuations in Suicidal Ideation and Its Risk Factors: Results From Two Ecological Momentary Assessment Studies" https://kleimanlab.org/wp-content/uploads/2018/11/Kleiman-et-al.-2017-Examination-of-Real-Time-Fluctuations-in-Suicidal-Ideation-and-Its-Risk-Factors-Results-From-Two-Ecological-Mome.pdf
Stress Risk Score (SRS)	It is a diagnostic tool that identifies urban stressors that have the most impact on the human biological system, specifically the stress response. These stressors have been qualified using scientific studies that focus on	The Purpose: 1. At this diagnostic stage, the aim is to understand what stressors are present in a given area 2. Have biologically based diagnostics to score an area, allowing mitigations to be based on human biology rather than only self-reporting data. 3. A stress risk score – understanding that an area has a risk of biological stress which in turn can lead to physical and mental health issues.	Araceli Camargo (the contact from the Centric Lab where the tool has been developed) indicated they can be contacted in July 2019 about this tool to talk about potential to utilise it in research.	Link to the technology company website: https://www.thecentriclab.com/ Scientific enquiries: Araceli Camargo araceli@thecentriclab.com

	the stress response, human physiology, and cognition.	Applications: 1. This data can be used to do a cross correlation with mental and physical health statistics, helping both academics and industry. 2. This can also be used to do more data led mitigations as there will be a better understanding what stressors to mitigate at building and area level.		
Cognitive Reflection Test	This measures cognitive reflection/analytic thinking.	Table 7 in this document.	To use this scale, it would suffice to design an online survey to administer online or via an smartphone app such as Mezurio	This researcher has run a lot of studies using this measure and is very familiar with the relevant theories: gordon.pennycook@uregina.ca
The Actively Open-minded Thinking about Evidence (AOT-E)	This measures willingness to change one's beliefs according to evidence.	Table 7 in this document.	To use this scale, it would suffice to design an online survey to administer online or via an smartphone app such as Mezurio	This researcher has run a lot of studies using this measure and is very familiar with the relevant theories: gordon.pennycook@uregina.ca
Wechsler Individual Achievement Test - Second UK Edition (WIAT-II UK)	Assessment of reading, language and numerical attainment in one test. Subtests: ▪ Word Reading	The *WIAT-II*^{UK} was standardised on children **aged 4 years to 16 years 11 months** in the UK. However, adult norms from the U.S study are available from **17 to 85 years** by simply purchasing the adult scoring and normative supplement for use with your existing materials.	Booklet	UK Pearson Assessment website: https://www.pearsonclinical.co.uk/Psychology/ChildCognitionNeuropsychologyandLanguage/ChildAchievementMeasures/WechslerIndividualAchievementTest-SecondUKEdition(WIAT-IIUK)/WechslerIndividualAchievementTest-

	▪ Reading Comprehension ▪ Pseudoword Decoding ▪ Numerical Operations ▪ Mathematical Reasoning ▪ Spelling ▪ Written Expression ▪ Listening Comprehension ▪ Oral Expression			SecondUKEdition(WIAT-IIUK).aspx The Psychometrics Center: https://www.psychometrics.cam.ac.uk/services/psychometric-tests/wiat-ii
Raven's Progressive Matrices	Measure of deductive ability ("the ability to make sense or meaning out of complex or confusing data; the ability to perceive new patterns and relationships, and to forge (largely non-verbal) constructs which make it easy to handle complexity")	Two formats for adults: • **Standard Progressive Matrices (SPM)** (for use with the general population) • **Advanced Progressive Matrices (APM)** (top 20% of the population) *Testing time:* *Timed (40 minutes) or untimed*	Booklet	UK Pearson Assessment website: https://www.pearsonclinical.co.uk/Psychology/AdultCognitionNeuropsychologyandLanguage/AdultGeneralAbilities/Ravens-Progressive-Matrices/Ravens-Progressive-Matrices.aspx The Psychometrics Center: https://www.psychometrics.cam.ac.uk/services/psychometric-tests/raven
UK Version of the Watson-Glaser	• Analyse, interpret and	*Testing time:* *30 minutes timed*	Booklet	Pearson TalentLens website:

Critical Thinking Appraisal	draw logical conclusions from written information. • Recognise assumptions from facts. • Evaluate the strength of arguments. • Draw correct inferences.			https://www.talentlens.co.uk/product/watson-glaser/ The Psychometrics Center: https://www.psychometrics.cam.ac.uk/services/psychometric-tests/critical-thinking
Rust Advanced Numerical Reasoning Appraisal (RANRA)	Measures higher-level numerical reasoning skills	The RANRA Preparation Package consists of: • RANRA - Comparison of quantities • RANRA – Sufficiency of Information • Watson Glaser Critical Thinking Test	Online tests	https://www.assessment-training.com/ranra
Cognitive Offloading	Prospective memory represents a form of memory that involves remembering to perform a planned action or recall a planned intention at some future point in time.	Measures how we "offload" memories and intentions into external devices, e.g., set a smartphone reminder for an upcoming appointment rather than remember it using unaided memory. Technological advances enable use of smartphone and wearable devices reminders. The ability to fulfil delayed intentions is increasingly supported by external devices An individual's choice to use one may be based on diverse metacognitive processes and other factors.	Online / web based Gilbert (2015): https://www.sciencedirect.com/science/article/pii/S1053810015000070 Demo of the task used in these studies: https://www.ucl.ac.uk/sam-gilbert/demos/circleDemo.html Optimal use of reminders: https://psyarxiv.com/7fxrg/ Task used: http://samgilbert.net/optimalDemo/start.html	Contact person: Sam.gilbert@ucl.ac.uk

University of Cambridge Psychometrics Center (Apply Magic Sauce)	This tool builds a psychological profile from an individual's digital footprint from Facebook and Twitter data.	This is a tool developed to investigate aspects of digital behaviour. It uses an individual's digital footprints to predicts that individual's psychological profiles, psychological traits and emotions that drive their behaviour. To do so, it uses online data from participants' Facebook and Twitter accounts. Thus, it seems incorporating this tool can significantly expand the breadth, detail and interpretability of one's measurements. On the tool's website it is claimed this tool was proven to know better than one's colleagues, friends, family and romantic partners. If you are conducting academic research, you can use the API for your project. You have to sign up on their website and tell them about your project. They want to know that your participants or users have consented, or will consent, to their data being used for the purpose of prediction. They can also offer advice on how to design your study or application based on their research experience that you may find useful.	Online / web based	https://applymagicsauce.com/research

Table 2: Cambridge Brain Sciences

Domain	Tests	Description	Tasks	Links to Test
Concentration	Double Trouble	Response Inhibition Based upon the Stroop task	“Three words appear on the screen: one at the top and two at the bottom. The user's job is to click on the word at the bottom that correctly describes the colour of the word at the top—for example, if the word at the top says “BLUE” but is written in red, the patient must inhibit the tendency to read what the word says, and instead click the word “RED.””	https://www.cambridgebrainsciences.com/science/tasks/double-trouble
	Feature Match	Attention	“Two boxes appear on the screen, each containing an array of abstract shapes. The patient must determine if the boxes are identical or different and click the appropriate button. Difficulty adjusts to the patient’s performance, ensuring the task is consistently challenging.”	https://www.cambridgebrainsciences.com/science/tasks/feature-match
Reasoning	Odd One Out	Deductive Reasoning “Requires reasoning about the features of several shapes to deduce the one shape that does not fit in with the rest.”	“Nine sets of shapes appear on the screen, different from each other in color, shape, and number. The user must pay close attention to how the shapes differ from each other, and point out the one shape that is most different from the rest. In some cases, like when there is only one red shape, the answer is obvious. However, the task gets more difficult with each correct answer, and harder puzzles require comparing several different features at the same time.”	https://www.cambridgebrainsciences.com/science/tasks/odd-one-out
	Polygons	Visuospatial processing “Polygons challenges the patient’s proficiency in picking out subtle differences between shapes.”	“Two panels appear. One contains two overlapping shapes, and one contains just one shape. The patient must determine if the single shape is identical to one of the overlapping shapes, or if it is subtly different than both shapes. Puzzles get more difficult with every correct answers.”	https://www.cambridgebrainsciences.com/science/tasks/polygons

	Rotations	Mental rotation “Effectively manipulating mental representations of objects allows people to make valid conclusions about what objects are and where they belong.”	“Two boxes appear on the screen, each filled with red and green squares. The patient must determine if the boxes would be identical if one of them could be rotated. More squares are added each time the patient answers correctly, increasing the difficulty.”	https://www.cambridgebrainsciences.com/science/tasks/rotations
	Spatial Planning	Planning “Spatial Planning assesses the patient’s ability to act with forethought and sequence behaviour in an orderly fashion to reach specific goals.”	“A tree-shaped frame appears on the screen with 9 numbered balls slotted onto the branches. The patient must rearrange the balls so that they are slotted onto the branches in numerical order, in as few moves as possible. Puzzles get more difficult as the patient gets correct answers.”	https://www.cambridgebrainsciences.com/science/tasks/spatial-planning
Short-Term Memory	Monkey Ladder	Visuospatial working memory “Requires storing numbers and their locations, then translating that memory into a series of movements in space.”	“Boxes appear at different locations on the screen, each containing a number. Your patient must try to remember which numbers appear in which box. After a short time, the numbers disappear, and the patient clicks on the boxes in numerical sequence. Difficulty adjusts to the patient’s performance, and performance is indicated by the average number of boxes correctly remembered.”	https://www.cambridgebrainsciences.com/science/tasks/monkey-ladder
	Paired Associates	Episodic Memory “Assesses episodic memory by asking patients to remember which objects they previously saw, along with the location where they were seen.”	“A set of boxes appear on the screen. They will open, one after the other, revealing the objects inside. The patient must remember which object appeared in which box. Next, one at a time, objects appear in the center of the screen, and patients must point out which box each object was located in. The number of boxes increases with correct answers, and performance is indicated by the average number of boxes correctly remembered.”	https://www.cambridgebrainsciences.com/science/tasks/paired-associates

	Spatial Span	Spatial short-term memory "Spatial Span challenges the patient's ability to remember the relationships between objects in space, as opposed to verbally rehearsing items in specific order, which relies on verbal short-term memory."	"A grid of boxes appears on the screen. The patient's job is to pay attention when the boxes begin flashing in sequence, then click the boxes in the same sequence. If correct, the next sequence will be one box longer. Performance is indicated by the average number of boxes remembered during the task."	https://www.cambridgebrainsciences.com/science/tasks/spatial-span
	Token Search	Working Memory "In Token Search, patients need to maintain and update an ongoing representation of previous searches in a self-directed task."	"Several boxes appear on the screen. The patient must click boxes to search them, looking for a token. The process repeats when a token is found, but the box where a token was previously found cannot be searched again, requiring ongoing updates to the representation of the boxes in memory. Correctly finding a token in every box will present a new puzzle with more boxes, and performance is indicated by the average number of boxes found."	https://www.cambridgebrainsciences.com/science/tasks/token-search
Verbal	Digit Span	Verbal short-term memory "Digit Span involves numbers, but performance is indicative of verbal short-term memory, because it requires dealing with items in a specific order, as opposed to spatial short-term memory."	"A sequence of numbers appears on the screen, one at a time. At the sound of the beep, users click the numbers in the same order. The number of digits increases with correct answers, and performance is indicated by the average number of digits correctly remembered."	https://www.cambridgebrainsciences.com/science/tasks/digit-span
	Grammatical Reasoning	Verbal Reasoning	"A statement appears at the top of the screen, and two objects underneath. The patient's task is to reason about the relationships among the objects and determine if the	https://www.cambridgebrainsciences.com/science/tasks/grammatical-reasoning

		"While language comes naturally to most people, understanding complex sentences with multiple negative statements is consistently challenging."	statement is true or false. Responding quickly and accurately is required for high scores."	

Table 3: ACE Explorer (Adaptive Cognitive Evaluation)

Domain	Construct Measured	ACE Explorer Task	Description	More Information
Basic Response Time	Basic Response Time	Basic Response Time *Gameplay Time: 2 minutes*	"The Basic Response Time module is designed to index the basic response speed of participants. Participants are instructed to identify the ACE symbol (target) always appearing in the center of the screen without distraction by tapping a button each time the symbol appears. Participants complete 20 trials of this game."	Link to Tasks Details for all these tests.
Attention	Response Inhibition	Colour Tricker (Stroop) *Gameplay Time: 3 minutes*	"The Stroop Module is designed to measure response inhibition performance. Participants view colored words and are instructed to identify the color of the word (target) and ignore the color the word spells (distractor). Participants complete 50 trials, 70% incongruent trials in which the color of the word does not match the color it spells, and 30% congruent trials in which the color of the word matches the color the word spells."	
	Selective Attention	Flanker *Gameplay Time:*	"The Flanker Module is designed to measure selective attention and interference resolution performance. Participants view an array of five letters and are instructed	

		3 minutes	to identify the central letter (target) and ignore the flanking letters (distractors). Participants complete 50 trials, 50% congruent trials in which the distractors and target match, and 50% incongruent trials in which the distractors differ from the target."
	Sustained Attention Impulse Control	UFO (SAAT) *Gameplay Time: 3 minutes*	"The SAAT Module is designed to measure both sustained attention and impulsivity. Participants view the ACE symbol appear on the top of the screen (target) or bottom of the screen (distractor). Participants are instructed to press a button when the target appears at the top of the screen, and ignore the symbol when it appears on the bottom. Participants complete 40 trials, 50% of which are impulsivity trials (i.e., target appears 66.6% of the time), and 50% of which are sustained trials (i.e., target appears 33.3% of the time)."
	Directed / Selective Attention	Compass (Spatial Cueing) *Gameplay Time: 3 minutes*	"Spatial cueing is designed to measure selective attention. Participants are instructed to look at the center of the screen where they will show an arrow pointing to the likely location of a target UFO. Regardless of where the arrow is pointing, the participant must tap the button on the side corresponding to where the UFO appears. Participants complete 40 trials of this game."
	Emotion-Based Attention	Face Switch *Gameplay Time: 4 minutes*	"Face Switch is designed to measure emotion-based attention abilities, as it is a derivative of the attention dot probe task. Similar to the spatial cueing task, participants are asked to respond as quickly as possible to the target on the left or right of the screen. Prior to target display, an image of a face with a happy, neutral, or negative emotion is shown where the target will be; previous work has shown that these image types have direct effects on the response time to a target. Participants complete 40 trials of each type during this game."
Working Memory	Visuospatial working memory capacity	Gem Chaser (Forward Spatial Span)	"The Forward Spatial Span Module is designed to measure visuospatial working memory capacity. Participants view a test array of twenty black circles that

	Gameplay Time: *2 minutes*	are cued randomly (i.e., light up in green, one at a time). Participants are instructed to recall the cued circles, and during target trials, identify them by tapping each in the order they lit up. Participants complete two target trials per level, beginning with level 3 (i.e., three cued circles); then advance to the next level (i.e., Level 3, then 4, etc.) once the participant completes two consecutive trials of the previous level without error. Participants complete as many levels as possible."
Visuospatial working memory updating	Backwards Gem Chaser (Backwards Spatial Span) *Gameplay Time:* *3 minutes*	"The Backward Spatial Span Module is designed to measure visuospatial working memory capacity and manipulation performance. Participants view a test array of twenty black circles that are cued randomly (i.e., light up in blue, one at a time). Participants are instructed to recall the cued circles, and during target trials, identify them by tapping each in the reverse order they lit up. Participants complete two target trials per level, beginning with level 3 (i.e., three cued circles); then advance to the next level (i.e., Level 3, then 4, etc.) once the participant completes two consecutive trials of the previous level without error. Participants complete as many levels as possible."
Working memory fidelity	Color Swatch *Gameplay Time:* *3 minutes*	"Color Swatch is designed to measure working memory fidelity. Participants are instructed to memorize the (briefly) displayed 3 colors on the screen, and then asked to recall which of these colors were shown on the screen (out of 5 possible choices). Participants complete 40 trials of this game."
Visual working memory capacity and Distraction Filtering	Filter *Gameplay Time:* *4 minutes*	"The Filter Module is designed to measure visual working memory capacity and precision performance. Participants view an array of colored rectangles (red and blue) and are instructed to attend to the red and ignore the blue rectangles. Two or four red (target) rectangles always appear, along with 0, 2, 4 blue (distracting) rectangles. Participants are instructed to detect whether either of the red (target) rectangles change orientation from first to

			second presentation, and indicate if the target is in the same or different orientation.”
	Visual search working memory performance	Boxed *Gameplay Time: 5 minutes* (Breakdown of constructs measured: Visual search, Top-down Attention, Distraction Cost, Processing Cost)	“The Boxed Module is designed to measure visual search working memory performance. Participants view an array of colored landolt squares (red and green) with side openings (left, right, bottom, or top) and are instructed to attend to the green with top or bottom openings (target), and ignore all other red and green squares. Green squares with top/bottom openings always appear, along with 3 distractors (no green distractors; i.e., the feature 4 condition) in the first 25% of trials, 11 distractors (no green distractors; i.e., feature 12 condition) in the first 25% of trials, 3 distractors (both green and red distractors; i.e., the conjunction 4 condition) in the first 25% of trials, and 11 distractors (both green and red distractors; i.e., the conjunction 12 condition) in the last 25% of trials.”

Table 4: CANTAB Connect Research

Domain	Tests / Length / Outcome Measure	Description	Task	Link to Test
Attention & Psychomotor Speed	Reaction Time (RTI) *Administration time: 3 minutes* *Outcome measures:* → *Latency (speed of response)* → *Probability of false alarms* → *Sensitivity*	“Assessment of motor and mental response speeds” “Measures of movement time, reaction time, response accuracy, impulsivity”	“A white box is shown in the centre of the screen, inside which digits from 2 to 9 appear in a pseudo-random order, at the rate of 100 digits per minute. Participants are requested to detect target sequences of digits (for example, 2-4-6, 3-5-7, 4-6-8). When the participant sees the target sequence they must respond by selecting the button in the centre of the screen as quickly as possible. The level of difficulty varies with either one- or three-target sequences that the participant must watch for at the same time.”	https://www.cambridgecognition.com/cantab/cognitive-tests/attention/rapid-visual-information-processing-rvp/

	Rapid Visual Information Processing (RVP) *Administration time:* *7 minutes* *Outcome measures:* *→ Latency (speed of response)* *→ Probability of false alarms* *→ Sensitivity*	“Measure of sustained attention”	“A white box is shown in the centre of the screen, inside which digits from 2 to 9 appear in a pseudo-random order, at the rate of 100 digits per minute. Participants are requested to detect target sequences of digits (for example, 2-4-6, 3-5-7, 4-6-8). When the participant sees the target sequence they must respond by selecting the button in the centre of the screen as quickly as possible. The level of difficulty varies with either one- or three-target sequences that the participant must watch for at the same time.“	https://www.cambridgecognition.com/cantab/cognitive-tests/attention/rapid-visual-information-processing-rvp/
	Motor Screening Task (MOT) *Administration time:* *2 minutes* *Outcome measures:* *→ Speed of response* *→ Accuracy of pointing (selecting the cross)*	“General assessment of whether sensorimotor deficits or lack of comprehension, will limit the collection of valid data from the participant.”	“Coloured crosses are presented in different locations on the screen, one at a time. The participant must select the cross on the screen as quickly and accurately as possible.”	https://www.cambridgecognition.com/cantab/cognitive-tests/attention/motor-screening-task-mot/
Memory	Delayed Matching to Sample (DMS) *Administration time:* *7 minutes* *Outcome measures:* *→ Latency (speed of response)* *→ Number of correct patterns selected*	“Assesses both simultaneous visual matching ability and short-term visual recognition memory, for non-verbalizable patterns.”	“The participant is shown a complex visual pattern, that is both abstract and non-verbal (the sample), followed by four similar patterns, after a brief delay. The participant must select the pattern which exactly matches the sample. In some trials the sample and the choice patterns are shown simultaneously, in others there is a delay (of 0, 4 or 12 seconds) before the four choices appear.”	https://www.cambridgecognition.com/cantab/cognitive-tests/memory/delayed-matching-to-sample-dms/

	→ *Statistical measure giving the probability of an error after a correct or incorrect response*			
	Paired Associates Learning (PAL) *Administration time:* *8 minutes* *Outcome measures:* → *Errors made by the participant* → *Number of trials required to locate the pattern(s) correctly* → *Memory scores* → *Stages completed*	"Assesses visual memory and new learning."	"Boxes are displayed on the screen and are "opened" in a randomised order. One or more of them will contain a pattern. The patterns are then displayed in the middle of the screen, one at a time and the participant must select the box in which the pattern was originally located. If the participant makes an error, the boxes are opened in sequence again to remind the participant of the locations of the patterns. Increased difficulty levels can be used to test high-functioning, healthy individuals."	https://www.cambridgecognition.com/cantab/cognitive-tests/memory/paired-associates-learning-pal/
	Pattern Recognition Memory (PRM) *Administration time:* *4 minutes* *Outcome measures:* → *Number and percentage of correct trials* → *Latency (speed of participant's response)*	"Test of visual pattern recognition memory in a 2-choice forced discrimination paradigm."	"The participant is presented with a series of visual patterns, one at a time, in the centre of the screen. These patterns are designed so that they cannot easily be given verbal labels. In the recognition phase, the participant is required to choose between a pattern they have already seen and a novel pattern. In this phase, the test patterns are presented in the reverse order to the original order of presentation. This is then repeated, with new patterns. The second recognition phase can be given either immediately or after a delay."	https://www.cambridgecognition.com/cantab/cognitive-tests/memory/pattern-recognition-memory-prm/
	Spatial Working Memory (SWM) *Administration time:* *4 minutes*	This test has executive function demands and provides a measure of	"The test begins with a number of coloured squares (boxes) shown on the screen. The aim of this test is that by selecting the boxes and using a process of elimination, the participant should find one yellow 'token' in each of a number of boxes and use them to fill up an empty column on the right-hand side of the screen. Depending	https://www.cambridgecognition.com/cantab/cognitive-tests/memory/sp

	Outcome measures: → *Errors (selecting boxes that have already been found to be empty and revisiting boxes which have already been found to contain a token)* → *Strategy*	strategy and working memory errors.	on the difficulty level used for this test, the number of boxes can be gradually increased until a maximum of 12 boxes are shown for the participants to search. The colour and position of the boxes used are changed from trial to trial to discourage the use of stereotyped search strategies."	atial-working-memory-swm/
	Verbal Recognition Memory (VRM) *Administration time:* *10 minutes* *Outcome measures:* → *Number of distinct words for the free recall phase* → *Number of correct and incorrect responses for the immediate and delayed recognition parts of the task*	"Assesses verbal memory and new learning. It measures the ability to encode and subsequently retrieve verbal information, with recall tapping into fronto-temporal networks and recognition assessing hippocampal areas."	"The participant is shown a sequence of words on screen one by one. The participant is then tasked with recalling the words, whilst a rater marks which ones they remembered. In the next phase, the participant is presented with two words, one from the original list and one distractor and is asked to choose which one they have seen before, in a 2-force choice paradigm. The latter recognition phase is then repeated after a delay."	https://www.cambridgecognition.com/cantab/cognitive-tests/memory/verbal-recognition-memory-vrm/
Executive Function	Cambridge Gambling Task (CGT) *Administration time:* *18 minutes* *Outcome measures:* → *Measurements of risk-taking* → *Quality of decision-making* → *Decision time*	"Assess decision making and risk-taking behaviour outside a learning context."	"The participant is presented with a row of ten boxes across the top of the screen: some are red and some are blue. The ratio of red and blue boxes will vary between stages but there will always be one box that contains a yellow token. Participants must use the 'Red' and 'Blue' buttons at the bottom of the screen to choose the box colour in which they think the token is hidden. In the assessed stages, participants start with 100 points and select a proportion of these points to bet on their decision. A circle in the centre of the screen displays the current bet value, which will either incrementally increase or decrease (depending on the task variant	https://www.cambridgecognition.com/cantab/cognitive-tests/executive-function/cambridge-gambling-task-cgt/

	→ *Risk adjustment* → *Delay aversion* → *Impulsivity*		selected). Participants press this button when it shows the proportion of their score they would like to bet. These points will either be added or taken away to their total score, depending on their decision and where the token is actually hidden.“	
	Intra-Extra Dimensional Set Shift (IED) *Administration time:* *7 minutes* *Outcome measures:* → *Number of errors made* → *Number of trials completed* → *Number of stages completed* → *Latency*	“Test of rule acquisition and reversal. It features visual discrimination and attentional set formation maintenance, shifting and flexibility of attention. This test is sensitive to changes in the fronto-striatal areas of the brain and is a computerised analogue of the Wisconsin Card Sorting test.”	“Two artificial dimensions are used in the test: 1. Pink shapes 2. White lines In this task, participants must use feedback to work out a rule that determines which stimulus is correct. After six correct responses, the stimuli and/or rule changes. Initially the task will involve simple stimuli which are made up of just one of the dimensions e.g. two white lines that differ in shape. Later on in the task, compound stimuli are used: white lines overlaid on the pink shapes. The shifts in rule are initially intra-dimensional (i.e. the pink shapes remain the only relevant dimension) and then later extra-dimensional (i.e. white lines become the relevant dimension).”	https://www.cambridgecognition.com/cantab/cognitive-tests/executive-function/intra-extra-dimensional-set-shift-ied/
	Multitasking Test (MTT) *Administration time:* *8 minutes* *Outcome measures:* → *Response latency* → *Error scores that reflect the participant’s ability to manage*	“Test of the participant’s ability to manage conflicting information provided by the direction of an arrow and its location on the	“The test displays an arrow which can appear on either side of the screen (right or left) and can point in either direction (to the right or to the left). Each trial displays a cue at the top of the screen that indicates to the participant whether they have to select the right or left button according to the “side on which the arrow appeared” or the “direction in which the arrow was pointing”. In some sections of the task this rule is consistent across trials (single task) while in others it may change from trial to trial in a	https://www.cambridgecognition.com/cantab/cognitive-tests/executive-function/multitasking-test-mtt/

	multitasking and the interference of incongruent task-irrelevant information on task performance (i.e. a Stroop-like effect)	screen and to ignore task-irrelevant information."	randomised order (multitasking). Using both rules in a flexible manner places a higher demand on cognition than using a single rule. Some trials display congruent stimuli (e.g. arrow on the right side pointing to the right) whereas other trials display incongruent stimuli, which require a higher cognitive demand (e.g. arrow on the right side of the screen pointing to the left)."	
	One Touch Stockings of Cambridge (OTS) *Administration time:* *10 minutes* *Outcomes measures:* *→ Number of problems solved on first choice* *→ Mean choices to correct* *→ Mean latency (speed of response) to first choice* *→ Mean latency to correct* *"Each of these measures may be calculated for all problems, or for problems with a specified number of moves (one-move to five or six moves)."*	"Test of executive function, based upon the Tower of Hanoi test. It assesses both the spatial planning and the working memory subdomains."	"The participant is shown two displays containing three coloured balls. The displays are presented in such a way that they can be easily perceived as stacks of coloured balls held in stockings or socks suspended from a beam. This arrangement makes the 3-D concepts involved apparent to the participant and fits with the verbal instructions. There is a row of numbered boxes along the bottom of the screen. The test administrator first demonstrates to the participant how to move the balls in the lower display to copy the pattern in the upper display and completes one demonstration problem, where the solution requires one move. The participant must then complete three further problems, one each requiring two moves, three moves and four moves. Next the participant is shown further problems and must work out in their head how many moves the solutions require and then select the appropriate box at the bottom of the screen to indicate their response."	https://www.cambridgecognition.com/cantab/cognitive-tests/executive-function/one-touch-stockings-of-cambridge-ots/
	Spatial Span (SSP) *Administration time:* *5 minutes* *Outcome measures:*	"Assesses visuospatial working memory capacity."	"White squares are shown on the screen, some of which briefly change colour in a variable sequence. The participant must then select the boxes which changed colour in the same order that they were displayed by the computer (for the forward variant) or in the reverse order (for backward variant). The number of boxes in the sequence increases from two at the start of the test, to nine at the end and the sequence and colour are varied through the test."	https://www.cambridgecognition.com/cantab/cognitive-tests/executive-function/spatial-span-ssp/

	→ Span length (the longest sequence successfully recalled) *→ Errors* *→ Number of attempts* *→ Latency (speed of response)*			
	Stockings of Cambridge (SOC) *Administration time:* *10 minutes* *Outcome measures:* *→ Problem difficulty level reached* *→ Mean moves used* *→ Thinking time*	"Test of spatial planning that requires individuals to use problem-solving strategies to match two sets of stimuli."	"The participant is shown two displays. In each of these displays, three stockings - containing three coloured balls - are suspended from a beam. The two displays appear at the top and bottom of the screen. The balls are arranged in different patterns in each display. The participant must move the balls in the bottom display to copy the pattern shown in the top display. The balls are moved one at a time by selecting the required ball, then selecting the position to which it should be moved. The participant is instructed to make as few moves as possible to match the two patterns. Movement time is discounted in a distinct phase of task, in which participants simply copy moves made by the computer. The moves shown by the computer mimic the moves the participant made when originally solving the problem."	https://www.cambridgecognition.com/cantab/cognitive-tests/executive-function/stockings-of-cambridge-soc/
	Stop Signal Task (SST) *Administration time:* *20 minutes* *Outcome measures:* *→ Direction errors* *→ Proportion of successful stops* *→ Reaction time on Go trials* *→ Stop signal reaction time (SSRT)*	"Unique version of a classic approach to measuring response inhibition (impulse control)."	"The participant must respond to an arrow stimulus, by selecting one of two options, depending on the direction in which the arrow points. If an audio tone is present, the subject must withhold making that response (inhibition). The test consists of two parts: In the first part, the participant is introduced to the test and told to select the left-hand button when they see a left-pointing arrow and the right-hand button when they see a right-pointing arrow. There is one block of 16 trials for the participant to practice this. In the second part, the participant is told to continue selecting the buttons when they see the arrows but, if they hear an auditory signal (a beep), they should withhold their response and not select the button.	https://www.cambridgecognition.com/cantab/cognitive-tests/executive-function/stop-signal-task-sst/

			The task uses a staircase design for the stop signal delay (SSD), allowing the task to adapt to the performance of the participant, narrowing in on the 50% success rate for inhibition."	
Emotion & Social Cognition	Emotional Bias Task (EBT) *Administration time:* *4 minutes* *Outcome measures:* *→ Bias point - the proportion of trials selected as happy compared to the alternative emotion, adjusted to a scale of 0 to 15.* *"This is used to determine the extent and direction of the participant's bias."* *→ Latency measures* *→ Measures of how many times each emotion was selected*	"Detects perceptual bias in facial emotion perception."	"Participants view images of faces that are morphed between two emotions of varied intensities. The variants cover continuums from happy to sad, happy to angry or happy to disgusted. Each face is displayed for 150ms, followed by a two-alternative forced choice where they must select one of the two emotions."	https://www.cambridgecognition.com/cantab/cognitive-tests/emotion-and-social/emotional-bias-task-ebt/
	Emotion Recognition Task (ERT) *Administration time:* *6-10 minutes* *Outcome measures:* *→ Percentages and numbers correct or incorrect* *→ Overall response latencies, which can be looked at either*	"Measures the ability to identify six basic emotions in facial expressions along a continuum of expression magnitude."	"Computer-morphed images derived from the facial features of real individuals, each showing a specific emotion, are displayed on the screen, one at a time. Each face is displayed for 200ms and then immediately covered up to prevent residual processing of the image. The participant must select which emotion the face displayed from 6 options (sadness, happiness, fear, anger, disgust or surprise)."	https://www.cambridgecognition.com/cantab/cognitive-tests/emotion-and-social/emotion-recognition-task-ert/

	across individual emotions or across all emotions at once

Table 5: NIH Toolbox Cognition Battery – Ages 18+

Domain	Tests	Description	Task	Link
Attention & Executive Functioning	NIH Toolbox Flanker Inhibitory Control and Attention Test Age 12+ v2.1 *Test time: 3 minutes*	"This is a measure of executive function that measures attention and ability to inhibit automatic responses that may interfere with achieving goals."	"This task requires participants to focus on a particular stimulus while inhibiting attention to the flanking stimuli." "For older children and adults, arrows are flanked by two arrows on each side." "There are two types of trials, congruent and incongruent." "The congruent and incongruent trials are mixed."	Detailed information on each test here
Episodic Memory	NIH Toolbox Picture Sequence Memory Test Age 8+ Form A v2.1 NIH Toolbox Picture Sequence Memory Test Age 8+ Form B v2.1 NIH Toolbox Picture Sequence Memory Test Age 8+ Form C v2.1	"Cognitive processes involved in the acquisition, storage and retrieval of new information."	"This measure assesses episodic memory using sequences of pictured objects and activities that are presented in a particular order." "Participants put the pictures back into the sequence that was shown."	Detailed information on each test here

	Test time: *7 minutes per test*			
Working Memory	NIH Toolbox List Sorting Working Memory Test 7+ v2.1 *Test time:* *7 minutes*	"The ability to store information until the amount of information to be stored exceeds one's capacity to hold that information."	"This task assesses working memory or the capacity to process information across a series of tasks and modalities." "It requires the participant to sequence sets of visually and orally presented stimuli in size order from smallest to biggest." "Pictures of different foods and animals are displayed with both a sound clip and written text that names them."	Detailed information on each test here
Executive Function	NIH Toolbox Dimensional Change Card Sort Test Age 12+ v2.1 *Test time:* *4 minutes*	"Measure of executive function that assesses cognitive flexibility and attention."	"There are two target pictures presented; these vary along two dimensions – shape and colour." "Participants match sets of two test pictures that differ in colour to the target pictures – the relevant dimension for sorting is indicated by a cue word – "shape" or "colour"."	Detailed information on each test here
Processing Speed	NIH Toolbox Pattern Comparison Processing Speed Test Age 7+ v2.1 *Test time:* *3 minutes*	"Assesses the amount of information that can be processed within a certain unit of time. Items are simple so as to purely measure processing speed."	"It requires participants to discern whether two side-by-side pictures are the same or not." "Older children and adults choose YES or NO buttons on the screen."	Detailed information on each test here
Language	NIH Toolbox Picture Vocabulary Test Age 3+ v2.1 *Test time:* *4 minutes*	Assesses vocabulary comprehension. "Administered in a computer-adaptive test format."	"This measure of receptive vocabulary is administered in a computer-adaptive format." "The participant is presented with four pictures and hears an audio recording saying a word." "Respondents select the picture that most closely matches the meaning of the word."	Detailed information on each test here *Source: Gershon, Cook, Mungas, Manly, Slotkin, Beaumont, & Weinraub (2014)*

	NIH Toolbox Oral Reading Recognition Test Age 3+ v2.1 *Test time:* *3 minutes*	"This measure assesses a participant's ability to read and pronounce letters and words." "The administration is individualized using a computerized adaptive format."	"Participant is asked to read and pronounce letters and words as accurately as possible."	Detailed information on each test here *Source: Gershon, Cook, Mungas, Manly, Slotkin, Beaumont, & Weinraub (2014)*
NIH Toolbox Cognition Supplemental Measures – Ages 18+				
Immediate Recall	NIH Toolbox Auditory Verbal Learning Test (Rey) 8+ v2.0 *Test time:* *3 minutes*	"Measures immediate recall."	"Unrelated words presented via audio recording and participant recalls as many as possible."	
Processing Speed	NIH Toolbox Oral Symbol Digit Test 8+ *Test time:* *3 minutes*	"Measures speed of processing."	"Symbols on the screen are associated with a number, then presented with symbols without numbers."	

Table 6: Cogstate Research™

Domain	Tests	Task / Description	Source
Visual Motor Control	Chase the target	"The Chase test measures visual motor control using a "chase the target" paradigm. This test is usually presented immediately before the Groton	

	Administration time: *2 minutes (healthy controls)* *Outcome measures:* *→ Number of correct moves per second chasing the target*	Maze Learning Test to familiarize the participant with the grid and to gain a measure of visuo-motor speed. The Chase test uses the same size grid as the Groton Maze Learning Test (e.g., a 10 x 10 grid of tiles). A red target is presented in the top left tile; the participant must select this target to begin the test. The target will move randomly from tile to tile throughout the grid and the participant must chase it by selecting tiles one at a time. If the correct move is made, a green checkmark briefly appears. If the move is incorrect, a red cross is briefly revealed."	INFORMATION on this battery and tasks A large DATABASE with publications which used this battery / these tasks
Paired Associate Learning	Continuous Paired Associate Learning Test *Administration time:* *7 minutes (healthy controls)* *Outcome measures:* *→ Total number of errors across the seven rounds in the test*	"The Continuous Paired Associate Learning test measures visual memory using a paired associative learning paradigm. In this test, the participant must learn and remember the pictures hidden beneath different locations on the screen. In the first stage of the test the pre-test on-screen instructions ask: "In what locations do these pictures belong". A picture is presented in the centre of the screen. The participant taps the peripheral location of the picture and must remember its location. During the second stage of the test the same pictures are presented in the centre of the screen, however the peripheral location of each picture is hidden. The participant must tap on the peripheral location where the picture previously appeared."	
Psychomotor Function	Detection Test *Administration time:* *3 minutes (healthy controls)* *Outcome measures:* *→ Speed of performance (mean of the log10 transformed reaction times for correct responses)*	"The Detection test measures processing speed using a simple reaction time paradigm. The on-screen instructions ask: "Has the card turned over?". A playing card is presented face down in the center of the screen. The card flips over so it is face up. As soon as the card flips over the participant must press "Yes". The participant is encouraged to work as quickly as they can and be as accurate as possible."	
Executive Function	Groton Maze Learning Test *Administration time:* *7 minutes (healthy controls)*	"The Groton Maze Learning Test measures executive function using a maze learning paradigm. A 10 x 10 grid of tiles is presented to the participant on the screen. A 28-step pathway is hidden among these tiles. A blue tile indicates the start and a tile with red circles indicates the finish. The	

	Outcome measures: *→ Total number of errors made in attempting to learn the same hidden pathway on five consecutive trials during a single session*	participant must move one step at a time from the start toward the end by touching a tile next to their current location. If the correct move is made a green checkmark appears and if the move is incorrect a red cross is revealed. Once completed, they are returned to the start location to repeat the test and must try to remember the pathway they have just completed. The Groton Maze Learning Test is also available in a "Delayed Recall" version, which measures visual memory."
Attention	Identification Test *Administration time:* *3 minutes (healthy controls)* *Outcome measures:* *→ Speed of performance (mean of the log10 transformed reaction times for correct responses)*	"The Identification test measures attention using a choice reaction time paradigm. The on-screen instructions ask: "Is the card red?". A playing card is presented face down in the center of the screen. The card flips over so it is face up. As soon as it flips over the participant must decide whether the card is red or not. If it is red the participant should press "Yes", and if it is not red the participant should press "No". The participant is encouraged to work as quickly as they can and be as accurate as possible."
Verbal Learning	International Shopping List Test *Administration time:* *5 minutes (healthy controls)* *Outcome measures:* *→ Total number of correct responses made in remembering the list on three consecutive trials at a single session*	"The International Shopping List Test measures verbal learning using a word list learning paradigm. The participant is read a shopping list and must remember and recall as many items from the list as possible. The International Shopping List Test is also available in a "Delayed Recall" version, which measures verbal memory."
Visual Learning	One Card Learning Test *Administration time:* *6 minutes (healthy controls)* *Outcome measures:*	"The One Card Learning test measures visual memory using a pattern separation paradigm. The on-screen instructions ask: "Have you seen this card before in this test?". A playing card is presented face up in the center of the screen and the participant must decide whether they have seen the card before in this test. The participant is encouraged to work as quickly as they can and be as accurate as possible."

	→ *Accuracy of performance (arcsine transformation of the square root of the proportion of correct responses)*	
Working Memory	One Back Test *Administration time:* *4 minutes (healthy controls)* *Outcome measures:* → *Speed of performance (mean of the log10 transformed reaction times for correct responses)* → *Accuracy of performance (arcsine transformation of the square root of the proportion of correct responses)*	"The One Back test measures working memory using an n-back paradigm. The on-screen instructions ask: "Is the previous card the same?". A playing card is presented face up in the center of the screen. The participant must decide whether the card is the same as the previous card. If the card is the same the participant should press "Yes", and if it is not the same the participant should press "No". The participant is encouraged to work as quickly as they can and be as accurate as possible."
Set shifting (Executive Function)	Set-Shifting Test *Administration time:* *7 minutes (healthy controls)* *Outcome measures:* → *Total number of errors made during the test*	"The Set-Shifting test uses a set shifting paradigm to measure executive function. The on-screen instructions ask: "Is this a target card?". A playing card is presented face up in the center of the screen with the word "Number" or "Color" above it. If the word is "Color" the participant must guess whether the target card is black or red. If the word is "Number" the participant must guess whether the current number displayed on the card is correct. At the beginning of the test, the participant simply needs to guess whether the current card is the target card. If they think the card is the target card, the participant should press "Yes". If they think the card is not the target card, they must press "No". As the participant makes their guesses, feedback is provided and the next card is not displayed until a correct response has been made. Once the participant has made their way through a set of cards the hidden rule changes (e.g., from one color to the other color [intra-dimensional shift], or from color to number [extra-dimensional shift]). The participant is not told when these set-shifts occur, and they must learn the new target rule to proceed through the test. The participant is encouraged to work as quickly as they can and be as accurate as possible."

Emotion Recognition	Social-Emotional Cognition Test *Administration time:* *6 minutes (healthy controls)* *Outcome measures:* *→ Accuracy of performance (arcsine transformation of the square root of the proportion of correct responses)*	"The Social-Emotional Cognition Test measures emotional recognition using an odd-man out paradigm. The on-screen instructions ask: "Tap the odd one out". Four pictures are presented on the screen. One of these pictures will be different to the others and the participant must decide which picture is different and tap that picture. The participant is encouraged to work as quickly as they can and be as accurate as possible."
Working Memory	Two Back Test *Administration tine:* *4 minutes* *Outcome measures:* *→ Accuracy of performance (arcsine transformation of the square root of the proportion of correct responses)*	"The Two Back test measures working memory using an n-back paradigm. The on-screen instructions ask: "Is the card the same as that shown two cards ago?". A playing card is presented face up in the center of the screen. The participant must decide whether the card is the same as the card shown two cards previously. If the card is the same the participant should press "Yes", and if it is the same the participant should press "No". The participant is encouraged to work as quickly as they can and be as accurate as possible."

Table 7: Novel cognitive constructs that have not been implemented with an app

Domain	Tests	Description	Task	Source
Cognitive Reflection / Analytic Thinking	Cognitive Reflection Test	This is a behavioural measure of the propensity to	1) A bat and a ball cost $1.10 in total. The bat costs $1.00 more than the ball. How much does the ball cost? _____ cents [5 cents] (2) If it takes 5 machines 5 minutes to make 5 widgets, how long would it take 100 machines to make 100 widgets? ______ minutes [5 minutes]	(1)-(3) from (Frederick, 2005); (4)-(7) from (Thomson

<table>
<tr><td></td><td></td><td>critically evaluate outputs from intuitive processing and engage in effortful reflective/analytic thinking.</td><td>(3) In a lake, there is a patch of lily pads. Every day, the patch doubles in size. If it takes 48 days for the patch to cover the entire lake, how long would it take for the patch to cover half of the lake? _____ days [47 days]
(4) If you’re running a race and you pass the person in second place, what place are you in? [second place]
(5) A farmer had 15 sheep and all but 8 died. How many are left? [8]
(6) Emily’s father has three daughters. The first two are named April and May. What is the third daughter’s name? [Emily]
(7) How many cubic feet of dirt are there in a hole that is 3’ deep x 3’ wide x 3’ long? [0, it’s a hole]</td><td>& Oppenheimer, 2016)</td></tr>
<tr><td>Actively Open-minded Thinking about Evidence</td><td>The Actively Open-minded Thinking about Evidence (AOT-E)</td><td>This measures willingness to change one’s beliefs according to evidence.</td><td>Items 3, 4, 5, 7, & 8 are reverse scored.
<table>
<tr><th>Item #</th><th>Item</th><th>AOT Subscale</th></tr>
<tr><td>1</td><td>A person should always consider new possibilities.</td><td>AOT</td></tr>
<tr><td>2</td><td>People should always take into consideration evidence that goes against their beliefs.</td><td>AOT</td></tr>
<tr><td>3</td><td>It is important to persevere in your beliefs even when evidence is brought to bear against them. (rev)</td><td>Belief Identification</td></tr>
<tr><td>4</td><td>Certain beliefs are just too important to abandon no matter how good a case can be made against them. (rev)</td><td>Belief Identification</td></tr>
<tr><td>5</td><td>One should disregard evidence that conflicts with your established beliefs. (rev)</td><td>Belief Identification</td></tr>
<tr><td>6</td><td>Beliefs should always be revised in response to new information or evidence.</td><td>Belief Identification</td></tr>
<tr><td>7</td><td>No one can talk me out of something I know is right. (rev)</td><td>Dogmatism</td></tr>
<tr><td>8</td><td>I believe that loyalty to one's ideals and principles is more important than “open-mindedness”. (rev)</td><td>Openness-Values</td></tr>
</table></td><td>Source of AOT-E scale: Pennycook, Cheyne, Koehler, and Fugelsang (2019) (working paper). Related versions: Baron, Scott, Fincher and Emlen Metz (2015); Haran, Ritov, and Mellers (2013)</td></tr>
</table>

Table 8: Useful resources

Name	Description	Contact/More Info
Technology, Mind and Society Conference	OCTOBER 3–5, 2019, GRAND HYATT WASHINGTON, WASHINGTON, DC Registration open till Oct 2nd the latest	https://www.apa.org/members/your-focus/science/technology-mind-and-society-conference/index
LDC 2019 **UbiComp 2019 Workshop on Longitudinal Data Collection**	Selected high-quality, high-impact, and original research results papers will be invited to submit extended version of their work to the Special Issue on 'Longitudinal Data Collection' of a journal (TBC).	https://ldc2019ubicomp.wordpress.com/ https://www.qualityoflifetechnologies.com/event/ldc-2019-ubicomp/
UbiComp	Ubiquitous Computing Conferences	http://ubicomp.org/ubicomp2019/
Pervasive Computing	Conference for presenting scholarly research in pervasive computing and communications	http://www.percom.org/
Workshops at UbiComp2019	A variety of workshops some of which may be relevant to the Centre of Longitudinal Studies work. UbiComp workshops are organized each year.	http://ubicomp.org/ubicomp2019/program_workshops.html
SIGCHI	The premier international society for professionals, academics and students who are interested in human-technology and human-computer interaction.	https://sigchi.org/about/about-sigchi/
Big Data in Psychology: Introduction to the Special Issue	Has lots of guidance on big data and the variety of algorithms applied for various analysis.	https://psycnet.apa.org/fulltext/2016-57141-001.pdf

Table 9: Relevant journals

Journal Name	Journal Website
Pervasive and Mobile Computing (Elsevier)	https://www.journals.elsevier.com/pervasive-and-mobile-computing/
IEEE Transactions on Affective Computing	https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=5165369
Big Data in Psychology, a special issues	https://www.apa.org/pubs/journals/special/2272104
Big Data	https://home.liebertpub.com/publications/big-data/611/overview
Ad Hoc Networks	https://www.journals.elsevier.com/ad-hoc-networks/
Computer Networks	https://www.journals.elsevier.com/computer-networks
Computer Communications	https://www.journals.elsevier.com/computer-communications/
Network Science (Cambridge University Press)	https://www.cambridge.org/core/journals/network-science
Journal of Complex Networks (Oxford University Press)	https://academic.oup.com/comnet
IEEE Transactions on Mobile Computing	https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=7755
IEEE Transactions on Parallel and Distributed Systems	https://www.computer.org/
IEEE Transactions on Information Technology in BioMedicine	https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=4233

IEEE Transactions on Industrial Informatics	https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=9424
ACM Transactions on Autonomous and Adaptive Systems	https://taas.acm.org/
ACM Transactions on Sensor Networks	https://tosn.acm.org/
EPJ Data Science (Springer)	https://epjdatascience.springeropen.com/
IEEE Journal on Selected Areas in Communications	https://www.comsoc.org/
IEEE/ACM Transactions on Networking	https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=90
ACM Transactions on Intelligent Systems and Technology	https://tist.acm.org/
ACM Transactions on Spatial Algorithms and Systems	https://tsas.acm.org/

Table 10: Information on relevant companies and databases

Name	Description	More Information
Quality of Life (QoL)	They research and develop mobile applications and services aimed at improving the quality of life of individuals throughout their lives.	https://www.qualityoflifetechnologies.com/

mQoL Living Lab	Dataset Overview: This website contains a high level overview of all data being collected from smartphone. The variables captured are represented here: https://www.qualityoflifetechnologies.com/app/uploads/2019/06/mQoL-log2019.png	https://www.qualityoflifetechnologies.com/living-lab/about-the-lab/data-collection-overview/ De Masi and Wac (2018, October): https://dl.acm.org/citation.cfm?doid=3267305.3267544
AWARE	This website contains overview of all data being collected from smartphone.	https://awareframework.com/sensors/
International Cognitive Ability Resource (ICAR)	This is a public-domain assessment tool; this database contains a broad range of assessment measures of cognitive abilities. To access this database, you first need to make an account. Then you will have access to their wiki page and the list if items for assessing cognitive abilities that have been contributed to the database. To gain full access to the test(s) you intend to use, you have to submit an application for the test(s).	https://icar-project.com/
IDTechEx	There is some information available for free. However, full reports need to be bought. This company does research about each emerging technology and their trends. They have reports with detailed results on application areas, providers, past trends and historic market data, and market 10 year forecasts. (Technology relevant to data collection at Centre of Longitudinal Studies: Wearable Technology, Sensors & Haptics, Life Sciences)	https://www.idtechex.com/en/research
European Network of Living Labs	"The European Network of Living Labs (ENoLL) is the international federation of benchmarked Living Labs in Europe and worldwide." – description on their website "Living Labs are defined as user-centred, open innovation ecosystems based on systematic user co-creation approach, integrating research and innovation processes in real life communities and settings." – description on their website	https://enoll.org/network/living-labs/
DamnFire	London-based tech company that is able to programme apps for measuring domains of cognition.	https://damnfine.com/work/
Akili	They build technologies referred to as digital medicine. The video games they build target domains of cognition which are affected in conditions likes: Attention Deficit/Hyperactivity Disorder (ADHD), Autism Spectrum Disorder (ASD), Major Depressive Disorder (MDD), Multiple Sclerosis (MS), and numerous other medical conditions	https://www.akiliinteractive.com/programs-products

Cognionics	They have mobile EEG products that can monitor neurophysiology in a wireless manner.	https://www.cognionics.net/
Neuroelectrics	They create products that represent diagnostic and treatment telemedicine wireless platforms based on Starstim and Enobio, combining multichannel transcranial current stimulation such as tDCS with EEG (i.e. mobile brain signal sensing and stimulation systems)	https://www.neuroelectrics.com/
Brain Vision	EEG products for neurophysiological research	http://brainvision.co.uk/

Table 11: Wearable Technology

Wearables	Description	More information
Notch	Records motion via Notches, sensor devices. Utilises an app which captures the Notch 3D motion data in real-time. Then you can watch on your phone an avatar perform a 3D visualization of your movements, you can export the motion data and analyse it.	https://wearnotch.com/
BTSBioengineering	Captures motion, have integrated systems to analyse motion, can dynamically analyse muscle activity.	https://www.btsbioengineering.com/products/freeemg/
dorsaVi	Can monitor posture and movement during daily activities and can provide motion-sensor feedback. Can collect raw data.	https://www.dorsavi.com/ There has been scientific papers published using their wearable technologies and they are open to talk with researchers who want to find out how wearable technology can be used for research, both in and out of the lab.
empatica	Medical Wearable. Monitors Autonomic Nervous System. They measure Electrodermal Activity to detect possible Epilepsy seizures. It also provides rest and physical activity analysis.	https://www.empatica.com/

BITalino	From here you can purchase different pieces of material that you put together to design your own wearable tool (hardware and software). They cover a variety of sensors.	https://bitalino.com/en/
Gait Up	Wearable motion sensors. They provide objective measures on gait analysis and running analysis and have inertial sensors. Standalone recordings or Wireless data streaming mode, Wireless data transfer	https://gaitup.com/products/physilog-sensor/ These products have a lot of scientific applications in different science domains, including Neurology.
MOOV	Fitness Wearable Variety of products, can capture and analyse motion in 3D Heart Rate readings and abalysis	https://welcome.moov.cc/
eSense	They are sharing the products with researchers to explore. Multi-sensory earable platform for personal-scale behavioural analytics research	http://www.esense.io/ Open to work with researchers on earable computing research Scientific paper: https://ieeexplore.ieee.org/document/8490189
HEY	Wearable that mimics human touch. Haptic communication (i.e. touch)	https://heybracelet.com/