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New Horizons in Neuropsychological Assessment: A Systematic Review on the Availability of Digital Tools for the Assessment of Attentive Abilities and Executive Functions in Adults

Supervisor
Professor Bonato Mario

Co-supervisor
PhD Candidate Vincenzo Livoti

Candidate: Matteo Vitacca
Student ID number: 2069466

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1. Introduction

1.1. Modern problems, modern solutions

Since the birth of neuropsychology, assessment of cognitive functions has been of crucial relevance for the investigation of the complex relationship between the mind and the brain, both in pathological and healthy conditions. While first attempts to measure consistently and reliably cognitive functioning mainly relied on direct observation of overt symptoms derived from neurological conditions, the need for more specific measurements both in clinical practice and in research led to the development of standardised paper-and-pencil tests. The idea was simple yet of extreme success; to challenge the patient/client by tapping into specific cognitive functions with verbally delivered instructions for tasks designed to isolate distinct cognitive processes. The ultimate goal being to gain valuable insights on the nature of cognitive impairments to inform and orient differential diagnosis and rehabilitation. Thanks to these tools we shed light on the nature of the diverse and yet entangled mechanisms governing cognition and refined our knowledge of the variable manifestations of neural pathologies.

Traditional paper-and-pencil neuropsychological tests, though, face several and important limitations. They are time-consuming, expensive, and require trained personnel for administration and interpretation, limiting their widespread use (Collie & Maruff, 2003). These tests often lack specificity, potentially missing important aspects of cognitive dysfunction (Kessels, 2019). Some have limited normative data, validity, or reliability, and may not adequately represent certain cognitive domains, especially high-level ones and social skills (Howieson, 2019). Additionally, they most often suffer from low ecological validity, deviating from real-world activities (Howieson, 2019; Kessels, 2019). Computerised tests have been developed over the last 30 years to address some of these issues, but they still face challenges such as lengthy administration times, technical limitations, and reliance on reaction times (Kessels, 2018). To overcome these limitations, researchers are exploring novel digital technologies like ecological momentary assessment, smartphone-based tools, wearable devices, and voice biomarkers, which offer potential improvements in data collection frequency and ecological validity (Harris et al., 2024).

The traditional neuropsychological assessment methods face several significant limitations, primarily due to the infrequent data collection that typically occurs during single in-person visits (Zucchella et al., 2018). Even when assessments are repeated, they are often spaced months or years apart, making it difficult to detect short-term cognitive fluctuations or changes that may occur on a daily or weekly basis(Kiselica et al., 2024). This limitation is particularly problematic for conditions with relapsing-remitting courses, such as multiple sclerosis, where timely detection of changes could lead to more effective interventions (Higginson et al, 2020). Furthermore, these assessments are conducted in controlled environments, reducing their ecological validity and failing to account for contextual factors like stress, fatigue, mood, or time of day, which can influence cognitive performance (Burgess et al., 1998, 2006). This gap may contribute to discrepancies between subjective cognitive complaints and objective test scores (Barker-Collo & Purdy, 2013; Bouazzaoui et al., 2010). Additionally, traditional assessments are time-consuming, limiting patient access and leading to long wait times (Higginson et al., 2000). Other issues include subtle variations in test administration by different raters, linguistic and cultural biases, and the reliance on retrospective self-reports in psychopathology assessment, which are prone to recall bias (Chiao & Cheon, 2010). These limitations highlight the need for high-frequency, real-world data collection, potentially facilitated by digital technologies, to improve the accuracy and accessibility of neuropsychological assessments (Harris et al., 2024).

1.2. A NEW HORIZON FOR NEUROPSYCHOLOGICAL ASSESSMENT

Digital tools offer several advantages for neuropsychological assessment. They provide standardised stimulus presentation, automatic scoring, and increased precision in measurements (Spreij et al., 2020), virtually infinite alternative versions of the same test to support longitudinal measurements. Digital assessments can reduce assessment time, minimize subjectivity, and allow clinicians to focus on treatment rather than test administration. They also have the potential to enhance accessibility and enable self-administration in non-clinical settings. Advanced technologies like virtual reality, in particular, show potential for more sensitive measurements thanks to their better ecological validity. Novel digital approaches, including ecological momentary assessment, smartphone-based tools, wearables, and voice biomarkers, can overcome limitations of traditional assessments by providing more frequent data collection and improved ecological validity (Harris et al., 2024). However, challenges remain, such as the need for new norms for digital versions of tests (Spreij et al., 2020) and potential issues with standardization across different hardware and software configurations. Furthermore, digital tools for neuropsychological assessment represent a more cost-effective method of data collection compared to paper-and-pencil tests (Chen et al., 2021).

More generally, digital tools offer many advantages; they provide results in real-time by yielding the scores instantly without the need of time-consuming correction, they require a shorter time for administration with respect to conventional tests, they can quantify with a high level of granularity the magnitude of improvement or deterioration within a certain cognitive domain, they can expand the spectrum of information acquired from a test by automatically recording reaction times, accuracy rates and combined measures, they are more suitable for test-retest designs thanks to automatic randomisation, they may be more engaging as presenting similar features to video-games and, finally, offer realistic scenarios to enhance the ecological validity of the tests themselves (Terruzzi et al., 2024).

1.3. ATTENDING THE UNATTENDED: THE CASE FOR NEGLECT

An emblematic example of the limitations of paper-and-pencil test is the case for subclinical neglect, where the ecological validity and diagnostic sensitivity of traditional tests was probed. Neglect, often referred to as hemispatial neglect or unilateral neglect, is a neurological condition typically following a stroke or brain injury, where a person fails to be aware of one side of space. Most commonly associated with damage to the right hemisphere of the brain, neglect affects the ability to attend to or respond to stimuli on the left side. Patients with neglect may ignore objects, people, or even parts of their own body located on the affected side. Neglect can severely impair daily life activities, such as dressing, eating, or navigating through environments. It often coexists with deficits in attention, particularly spatial attention, and can also affect a person's ability to multitask or maintain divided attention. This condition poses particular risks for tasks like driving or crossing the road, which require awareness of the full visual field (Heilman et al., 2000; Kerkhoff, 2001).

Indeed, paper-and-pencil commonly employed tests such as the cancellation and line bisection tests, do not prove to be sensitive enough to detect subclinical neglect (Bonato & Deouell, 2013) and have been criticised for their poor ecological validity since stimuli are static and presented in a narrow visual space. The cancellation test and the line bisection test are widely used to assess unilateral visuospatial neglect, particularly contralateral neglect, following a stroke or brain injury. In the cancellation test, patients are presented with a sheet filled with various symbols and are asked to mark or "cancel" all instances of a target symbol. Patients with contralateral neglect, often due to right hemisphere damage, typically miss symbols on the left side of the page, reflecting an attentional bias towards the right. Examples of the cancellation test include the Bells Test and the Star Cancellation Test, which are commonly employed to assess the severity of spatial neglect (Plummer et al., 2003, n.d.; Ferber & Karnath, 2001). The line bisection test, on the other hand, requires the patient to bisect horizontal lines drawn on a sheet of paper. Patients with contralateral neglect tend to mark the center of the line to the right of the actual midpoint, neglecting the left side of space. The extent of this deviation provides a measure of the severity of the neglect (Bonato et al., 2008).

Nevertheless, patients recovering from a stroke, especially when symptoms are not particularly severe, often develop compensatory strategies to compensate for the neurocognitive effects of the cardiovascular insult, thus passing brilliantly traditional paper-and-pencil tests. In contrast, computerised dual tasks (Bonato, 2015; Bonato & Deouell, 2013; Villarreal et al., 2020) offered the unique advantage of adaptability, thus brilliantly finding a way to expose the core residual visuospatial attention sources of post-stroke patients by overloading the attentional system with concomitant tasks (Bonato, 2012; Bonato et al., 2010). Under the assumption that neglect is a primarily attentional syndrome, this new methodological approach offered new insights into the nature of the functional impairment caused by strokes and challenged old beliefs such as the traditional idea that right-hemisphere strokes cause neglect while left wing strokes cause aphasic syndromes only (Blini et al., 2016). Indeed, adopting this sensitive computerised dual task, it was possible to show that left-hemisphere stroke patients developed subclinical neglect too. As the word ‘subclinical’ may improperly suggest that the effect of the organic condition do not predict significant impairment in daily life, it is important to remember that these patients often result unprepared to drive and conduct complex daily life activities which requires multi-tasking and divided attention (Bonato et al., 2010; Villarreal et al., 2020; Wolfe & Lehockey, 2016). These digital tools then, thanks to their scalable and adaptable nature, pave the way to a more personalised, precise, sensitive, specific and efficient approach to neuropsychological assessment.

1.4. NOT ALL THAT GLITTERS IS GOLD: LIMITATIONS AND OPEN ISSUES IN DIGITAL NEUROPSYCHOLOGICAL ASSESSMENT

While digital tools in neuropsychological assessment offer several advantages, such as increased accessibility, standardization, and the potential for more sensitive measurements (Parsey & Schmitter-Edgecombe, 2013), they do face some practical limitations. These include variability in perceptual, motor, and cognitive demands across different device types, as well as the impact of hardware and software on stimulus presentation. Additionally, rapid technological advancements can lead to test obsolescence (Germine et al., 2019). Digital approaches to neuropsychological assessments can indeed pose challenges to the clinician-patient relationship and limit the ability to observe patients during testing. One major concern is that digital tools reduce face-to-face interaction, which can hinder the establishment of a personal connection between the clinician and the patient. This connection is often vital for understanding subtle behavioural cues and emotional responses that could provide additional context to test results. Furthermore, the lack of direct observation in digital settings may lead to missed non-verbal signs or stress-induced behaviours that could affect cognitive performance (Donelan et al., 2019). Additionally, the use of digital platforms may create a barrier for clinicians in assessing patients' real-time reactions and nuances during testing, which are easier to capture in an in-person setting. This could limit the depth of patient observation, making it harder to tailor interventions or interpret results with full accuracy (Huxley et al., 2015). These factors emphasize the need for careful consideration when integrating digital tools into clinical practice, ensuring that they complement rather than replace essential observational techniques in patient assessment.

Finally, many digital tools lack strong evidence for reliability and validity, particularly in clinical populations. Despite these issues, digital neuropsychology holds promise for measuring cognitive functioning in everyday environments and over time (Germine et al., 2019). Emerging technologies like ecological momentary assessment, wearable devices, and voice biomarkers offer potential solutions to some of the limitations of traditional assessments, such as low-frequency data collection and ecological validity issues (Harris et al., 2024). However, detailed psychometric analysis and best practice guidelines for many digital approaches are still lacking. Moreover, many computerised paradigms validated for clinical use are merely digital adaptations of original paper-and-pencil tests and do not address several inherent limitations of traditional neuropsychological assessment (Harris et al., 2024).

1.5. A TENTATIVE TAXONOMY OF DIGITAL TOOLS

Digital cognitive assessment tools can be broadly categorised into three main types (Chen et al., 2023). The first category includes digital versions of traditional paper-and-pencil tests, such as the electronic Montreal Cognitive Assessment (eMoCA) [1] and the digital Clock Drawing Test (dCDT)[2] or the Wisconsin Card Sorting Test (WCST)[3] and Trail Making Test (TMT)[4] (Bayraktar et al., 2018; Miles et al., 2022; Steinke et al., 2021; Xu & Xian, 2023). While the conversion into digital versions of these established paper-and-pencil tools which are well validated and whose normative data are widely available, represents a positive step forward for the enhancement of neuropsychological assessment as it can support automatised scoring and storing of results, this category of digital tools represents an intermediate step in the evolution of neuropsychological assessment. Indeed, traditional paper-and-pencil tests show several limitations even when coming into their digital form, as they have been conceptualised in a way that does not allow to capitalise on the advantages of digitalisation. Additionally, in many cases paper-and-pencil tests are simply tele-administered (Alegret et al., 2021; Cullum et al., 2006; Jacobsen et al., 2003; Hernandez et al., 2022; Ramos-Henderson et al., 2022). While tele-administration is undoubtedly an invaluable approach for practical reasons, the simple tele-administration of traditional paper-and-pencil tests does not fully capitalise on the potentials of digital systems and integrated technologies (e.g., self-administered computerised batteries) which represent a more mature developmental stage of digital

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[1] **Electronic Montreal Cognitive Assessment (eMoCA)**: The eMoCA is a digital adaptation of the traditional MoCA, a widely used screening tool for detecting mild cognitive impairment. The digital version maintains the original test structure while offering benefits like automated scoring and accessibility on various devices (e.g., tablets or computers).

[2] **Digital Clock Drawing Test (dCDT)**: This digital version of the Clock Drawing Test, a classic neuropsychological assessment, analyzes not only the final drawing but also the process by which the clock is drawn. The dCDT is valuable for diagnosing cognitive impairments such as dementia, with the digital format capturing more detailed data than the traditional version.

[3] **Wisconsin Card Sorting Test (WCST)**: The digital WCST evaluates abstract reasoning and problem-solving abilities. It assesses a person's ability to adapt to changing rules, making it an important tool for measuring executive function. The electronic version maintains the integrity of the original while providing quicker feedback and enhanced data analysis.

[4] **Trail Making Test (TMT)**: The TMT, now available in digital form, measures cognitive flexibility, visual attention, and task-switching ability. The digital version speeds up administration and scoring while retaining the test’s core purpose, which is commonly used in the assessment of executive function.

neuropsychology. An exemplary instance of tele-administration of traditional paper-and-pencil tests it the development, prompted by the COVID-19, of virtual avatars, thanks to state-of-the-art speech synthesis and computerization techniques, to replace the experimenter/clinician and deliver all the verbal instructions to successfully carry out the tasks (Park & Etnier, 2021).

The second category consists of newly developed computerised neuropsychological tools and test batteries designed specifically for screening, comprehensive assessment, or diagnostic purposes. Among the most known and commonly employed, the Automated Neuropsychological Assessment Metrics (ANAM) (Ibarra, 2011), the NeuroTrax Computerised Cognitive Battery (Dwolatzky et al., 2003), the Cognitive Drug Research (CDR) Computerised Cognitive Assessment System (Keith et al., 1998), Cogstate (Maruff et al., 2009) and the Cambridge Neuropsychological Test Automated Battery (CANTAB) (Wild & Musser, 2014), which assess multiple cognitive domains. Cognitive batteries within this category generally come with normative data, high rates of reliability, validity and acceptability, thus standing out as great candidates for cognitive screening, repeated longitudinal assessments and multicentre studies.

Finally, the third category involves the use of new data streams and technologies, spanning from serious-games (Schilt et al., 2022), cognitive training programs with continuous measurements to support the adaptive modulation of task demands (Israsena et al., 2021), to virtual reality (VR) and augmented reality (AR) systems (Chicchi Giglioli et al., 2019; Foerster et al., 2019; Jansari et al., 2014; Kang et al., 2008; Malegiannaki et al., 2024; Voinescu et al., 2023) to assess cognitive functions. Another promising sub-category is represented by domain-specific computerised tools (Foxe et al., 2024), sometimes integrated with eye-tracking measures (Krebs et al., 2021; Leitner et al., 2023; Wong et al., 2019), to better characterise cognitive functions themselves in basic research and to identify distinct markers of cognitive deficits in neurological conditions such as behavioural variant frontotemporal dementia, post-stroke and Parkinson's disease in applied research settings. Driving simulators, despite their cost depending on the availability of specific tools and platforms such as steering-wheel and custom-designed foot-pedals, also constitute an interesting opportunity to assess the fitness to drive in older adults by assessing in a span of 15 minutes several cognitive domains crucial for safe driving such as selective and divided attention, executive functions, eye–hand coordination, distance judgment, and speed regulation (Bieri et al., 2014; Tinella, Caffò, et al., 2021). Finally, trained on computerised cognitive tests (Tang et al., 2024) or on functional electrophysiological signals (Wan et al., 2021), neural networks timidly begin to make their appearance, showing promising potential to enhance diagnostic sensitivity and predictive power in clinical settings. These innovative tools altogether leverage the possibilities for immersion offered by technology to offer novel and more ecological approaches to cognitive assessment.

1.6. ATTENTION

Attention is a fundamental cognitive function that enables optimal interaction with the environment through selective information processing and flexible response adaptation (Rueda et al., 2023). It encompasses multiple components, including alertness, spatial orienting, object feature processing, and endogenous control (Colombo, 2001). These attentional functions develop progressively during infancy, with rudimentary forms present at birth (Colombo, 2001). Attention has been conceptualised in terms of attentional resources, effort, and distributed neural networks (McDowd, 2007). It operates in various contexts, such as selective attention, divided attention, attention switching, and sustained attention (McDowd, 2007). The importance of attention in cognitive processes has led to its incorporation into neural network models across diverse applications (Chaudhari et al., 2021). Attention mechanisms in neural networks have not only improved performance but also enhanced interpretability (Chaudhari et al., 2021). Understanding the role of attention in cognition and its implementation in artificial systems continues to be an active area of research. Commonly used tests to evaluate attentive functions include the TMT Form A for assessing alternating attention, the Letter Cancellation Test for visual scanning and search, and the Digit Symbol Coding test for measuring sustained, selective, and divided attentional processes (Treviño et al., 2021).

Attention deficits have emerged as a significant predictor of cognitive impairment in older adults. Studies have shown that sustained attention tasks can effectively screen for cognitive impairment, with high sensitivity and specificity. In Parkinson's disease patients, attentional deficits were found to be the strongest predictor of declining quality of life over a three-year follow-up period. Similarly, individuals with mild behavioural impairment (MBI), a potential precursor to dementia, performed significantly worse on attention-related tasks compared to those without MBI (Rouse et al., 2021). Moreover, attention, along with short-term memory and temporal orientation, showed the greatest deterioration in older adults with cognitive impairment (Gómez-Soria et al., 2021). These findings collectively suggest that attention is a crucial cognitive domain for predicting and identifying cognitive decline in older adults, highlighting its potential as a target for early intervention and cognitive preservation strategies.

1.7. EXECUTIVE FUNCTIONS

Executive functions (EF) are complex cognitive processes that enable adaptive behaviour and goal pursuit (Fletcher, 1996). Research has identified several core components of EF, including working memory/updating, inhibition, and cognitive flexibility/shifting (Garon et al., 2008). These components interact, with working memory supporting inhibition and vice versa. Additional and more abstract aspects of EF include planning, problem-solving, self-monitoring, and mental set maintenance (Fletcher et al., 1996). Factor analysis of neuropsychological tests in traumatic brain injury (TBI) patients (Miyake et al., 2000; Spikman et al., 2017) revealed three EF factors: higher-order functions (self-generative behaviour and cognitive flexibility), mental control of working memory, and inhibition of inaccurate information (Busch et al., 2005). EF development begins in early childhood, with elementary forms of core components present in preschoolers (Garon et al., 2008) and matures in correspondence of the final stages of pre-frontal development during late adolescence/early adulthood. The central executive, conceptualised as a central control system directing the allocation of attentional sources and the interaction between components, is involved in all EF component operations (Garon et al., 2008).

Commonly employed traditional tests (Faria et al., 2015) to assess EF are the WCST (Grant & Berg, 1948), which focuses on cognitive flexibility with a set-shifting task, the TMT form B, probing task-switching (Partington & Leiter, 1949), the Verbal Fluency Test (VFT) - F, A and S; the VFT Animals category (Benton, 1969), which measure the ability to generate an appropriate strategy for word searching and retrieval, the Clock Drawing Test (CDT) (Critchley, 1953); the Digits Forward and Backward subtests, tapping into working and short-term memory, and the Stroop Test probing the fitness of inhibitory processes (Stroop, 1935). Other valuable traditional tools for the neuropsychological assessment of EF include the Tower of Hanoi (Welsh et al., 1999) and the Tower of London (Shallice, 1982), which assess planning abilities. These traditional tests have high construct and criterion validity and high test-retest reliability.

Executive functions (EF) have been shown to be significant predictors of functional independence in older adults, including those with cognitive impairments. A study found that EF moderates the relationship between physical performance and functional independence, with individuals having poor EF and mobility being at greater risk for functional decline (Dickens et al., 2015). Another study demonstrated a positive correlation between EF and functional independence in stroke patients (Arsic et al., 2016). Research has also indicated that EF, as measured by motor programming tasks, is an efficient predictor of functionality in community-dwelling older adults (Kraybill & Suchy, 2011). Furthermore, in a study of individuals with mild Alzheimer's disease and mild cognitive impairment, EF emerged as the only significant predictor of functional performance among various cognitive domains and depressive symptoms (Paula & Malloy-Diniz, 2013). These findings collectively emphasize the crucial role of executive functions in maintaining functional independence across different populations and conditions.

1.8. Open Science and the Importance of Availability and Accessibility

While the emergence of sophisticated digital technologies for more precise, sensitive, specific, and adaptable neuropsychological assessment is undoubtedly advancing the clinical field, the availability and accessibility of these tools have yet to be systematically assessed (Libon et al., 2023; Singh & Germine, 2021). Indeed, the high variety of software, applications, and web platforms running on a heterogeneous set of hardware, such as smartphones, tablets, computers, and wearable devices, while supporting a rich array of diverse tools, hinders their wide adoption and validation (Elson et al., 2019; Libon et al., 2023).

The availability of normative data, for instance, is fundamental for the consensual interpretation and certified use of assessment tools (Hunsley & Mash, 2007). Moreover, the availability of raw data would allow independent raters to test and verify the replicability of results, thereby enhancing the reliability and utility of tools for clinical practice (Munafò et al., 2017). The source code should be made available as well so to enable software developers to capitalise on previous work to create variants or to just improve existing tools (Ince et al., 2012). Moreover, the accessibility of digital tools should be promoted and valued, as it can greatly benefit professionals by reducing administration time and improving diagnostic sensitivity. Finally, reasoning along an open science framework, it is of pivotal importance to incentivize the sharing of information in the form of datasets, scripts, and procedures, making it possible for multi-centre, large-cohort, multicultural studies to become more common (Nosek et al., 2015).

2. Methods

2.1. Search strategy

A systematic review (SR) was conducted to examine the availability and accessibility of digital tools for assessing executive and attentional functions in the current literature, following PRISMA guidelines. The review aimed to provide an overview of the best available evidence regarding digital cognitive assessments. Articles without a time limitation were included in the search, focusing on three databases: PubMed, Embase, and Scopus.

The exclusion criteria for this study were meticulously defined to ensure the inclusion of relevant and high-quality assessments. Participants under 18 years of age were excluded to focus the study on the adult population, where cognitive assessments of attention and executive functions are most applicable. Non-validated digital tests were omitted to ensure that only reliable and standardised tools were considered, enhancing the validity of the findings. Assessments that did not evaluate specific components of attention or executive functions were excluded, as the study specifically aimed to analyze these critical cognitive domains. Furthermore, the study did not consider digital rehabilitation tools without an assessment module, since the primary focus was on assessment rather than intervention tools. Lastly, telephone-based assessments were excluded to maintain consistency in the modality of digital assessments evaluated, ensuring that all included tools shared similar technological platforms and user interfaces.

Each database was searched using a combination of relevant keywords, including "cognitive assessment," "cognitive evaluation," "neuropsychological evaluation," "neuropsychological assessment," "cognitive screening," "computer*," "web," "digital test," "tele*," "online," "attention," and "executive function*." The cognitive domains of interest were attention and executive functions, reflected in the search queries for each database:

1. **Embase:** ('cognitive assessment' OR 'cognitive evaluation' OR 'neuropsychological evaluation' OR 'neuropsychological assessment' OR 'cognitive screening') AND ('computer*' OR 'web' OR 'digital test' OR 'tele*' OR 'online') AND ('attention' OR 'executive function*')

    - Results: 841 articles identified.

2. **Scopus:** TITLE-ABS ("cognitive assessment" OR "cognitive evaluation" OR "neuropsychological evaluation" OR "neuropsychological assessment" OR "cognitive screening") AND ("computer*" OR "web" OR "digital test" OR "tele*" OR "online") AND ("attention*" OR "executive function*")

    - Results: 716 articles identified.

3. **PubMed:** ((cognitive assessment[Title/Abstract]) OR (cognitive evaluation[Title/Abstract]) OR (neuropsychological evaluation[Title/Abstract]) OR (neuropsychological assessment[Title/Abstract]) OR (cognitive screening[Title/Abstract])) AND ((computer*[Title/Abstract]) OR (web[Title/Abstract]) OR (digital test[Title/Abstract]) OR tele*[Title/Abstract]) AND ((attention*[Title/Abstract]) OR (executive function*[Title/Abstract]))

- Results: 583 articles identified.

The combined search across the three databases yielded a total of 2,140 results.

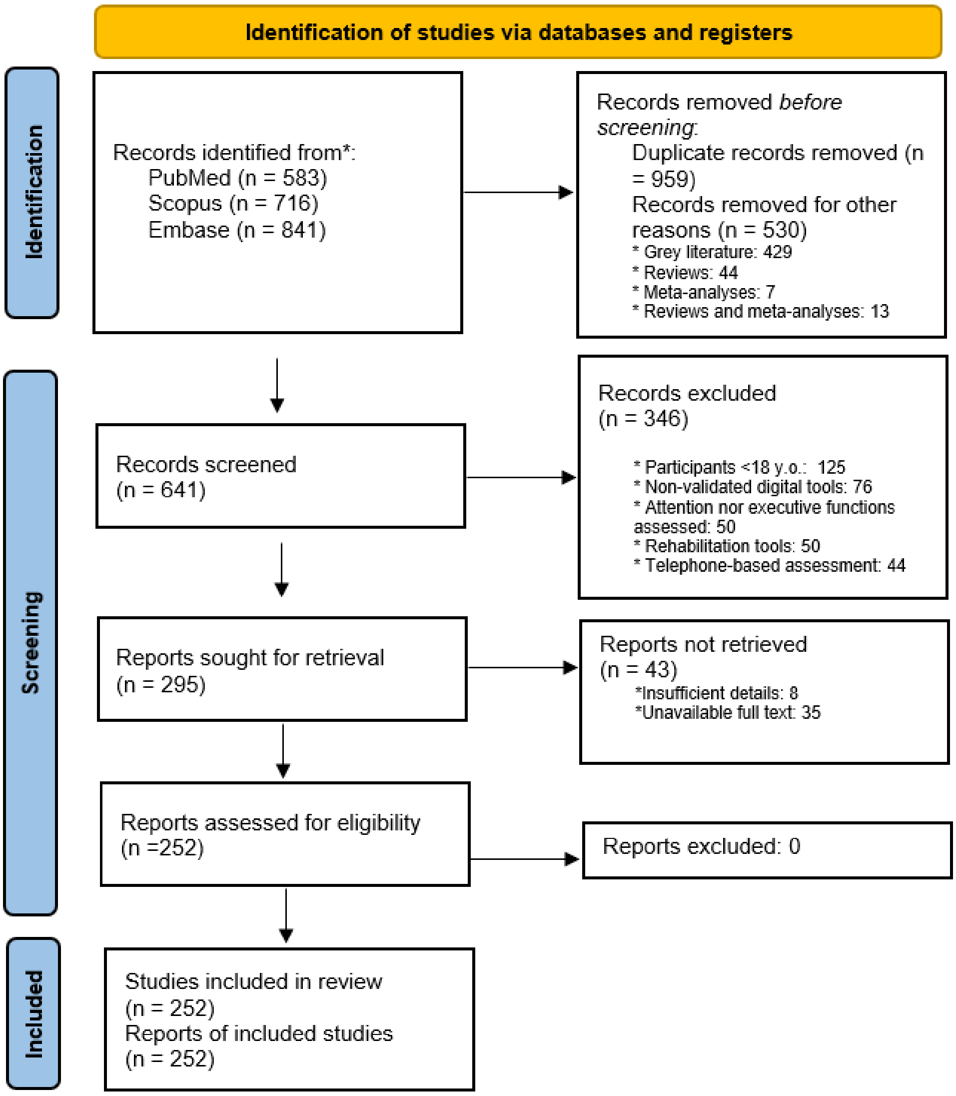


Figure 1 Flow diagram based on PRISMA method.

2.2. Duplicate Removal

Following automatic duplicate removal using Excel, the number of records was reduced to 1,682. A subsequent manual check for duplicates further reduced the dataset to 1,181 unique records.

2.3. Screening and Exclusion

The initial 1,181 papers underwent a screening process based on relevance to the aims of the study. The following categories of publications were excluded:

- Gray literature (conference abstracts, case reports, study protocols): 429 papers.
- Reviews: 84 papers.
- Meta-analyses: 7 papers.
- Review and meta-analysis combinations: 13 papers.

This process resulted in the identification of 641 papers for further review. Of these, 346 were excluded based on predefined exclusion criteria: 125 studies involved participants under the age of 18, 76 utilised non-validated digital tools, 50 did not evaluate specific components of attention or executive functions, 50 focused on rehabilitation tools without an assessment module, and 44 involved telephone-based assessments. Consequently, 295 papers were selected for full retrieval. Out of these 295 publications, 43 were not retrieved, as the full text could not be accessed for 35 of them and 8 that did not provide sufficient details about the implemented digital tools.

2.4. ELIGIBILITY ASSESSMENT

The 252 papers underwent a thorough eligibility assessment. The remaining **252 papers** were included in the final analysis, providing the basis for the systematic review.

These 252 studies were thoroughly examined to evaluate the application of digital tools in cognitive assessments, focusing specifically on attention and executive function. The final analysis also considered the technological characteristics of the tools and their clinical implications. This methodical review process ensured that only the most relevant and high-quality studies were included, thereby forming a solid foundation for evaluating the current landscape of digital neuropsychological assessments.

2.5. DATA EXTRACTION VARIABLES

To systematically analyze the relevant publications, a set of predefined variables of interest were used to extract key information from each study. These variables were selected to provide a comprehensive understanding of the characteristics and capabilities of the digital tools assessed, with a specific focus on availability of data and materials. The following variables were employed:

- **Administration:** This variable captures the mode of tool administration, which can be self-administered, conducted via telehealth (synchronous videoconference-based assessment), or supervised by a clinician.

- **Cognitive Functions Assessed:** Tools were categorised based on whether they assessed attention, executive functions (EF), or both. Additionally, we recorded any other cognitive functions assessed, such as memory or visuospatial abilities.

- **Language of Administration:** The language in which the assessment was administered, to account for potential linguistic and cultural variability and to assess the availability of digital tools across cultures.

- **Type of Tool:** This refers to the platform used for the assessment, including web-based platforms, mobile apps, desktop software, wearable devices, or hybrid platforms.

- **Device:** The type of device used to administer the digital tool, such as computers, tablets, smartphones, or multi-platform tools capable of functioning across different devices.

- **Website of the Tool:** Where applicable, the website or URL associated with the digital tool was recorded.

- **Accessibility of Digital Tools:** We categorised tools based on their accessibility, including those that are free and open access, restricted access, or require particular platforms or equipment.

- **Normative Data:** Whether the tool had normative data available, which is crucial for interpreting test results against standard populations (yes, no).

- **Availability of Normative Data:** This variable indicates whether normative data were readily available, available upon request, or integrated within the tool.

- **Availability of Study Data:** Whether the data collected in the study were publicly available, accessible upon request, or not available at all.

- **Data / Supplemental Materials:** Any links to the dataset or supplemental materials were recorded where available.

- **Availability of Code/Scripts:** Whether the code or scripts used in the study were available, either publicly, upon request, or not at all.

- **Source of Code/Scripts:** If applicable, the link to the source of the code or scripts used in the digital tool was documented.

- **Tool Name:** The specific name of the digital tool was recorded for identification purposes.

- **Clinical Population:** The specific clinical population targeted by the tool, if applicable, was also noted (e.g., Alzheimer's disease, multiple sclerosis).

2.6. ETHICAL CONSIDERATIONS

As the study did not involve direct contact with human participants, the need for ethical approval was not applicable. This systematic review was registered in accordance with recommended guidelines.

3. Results

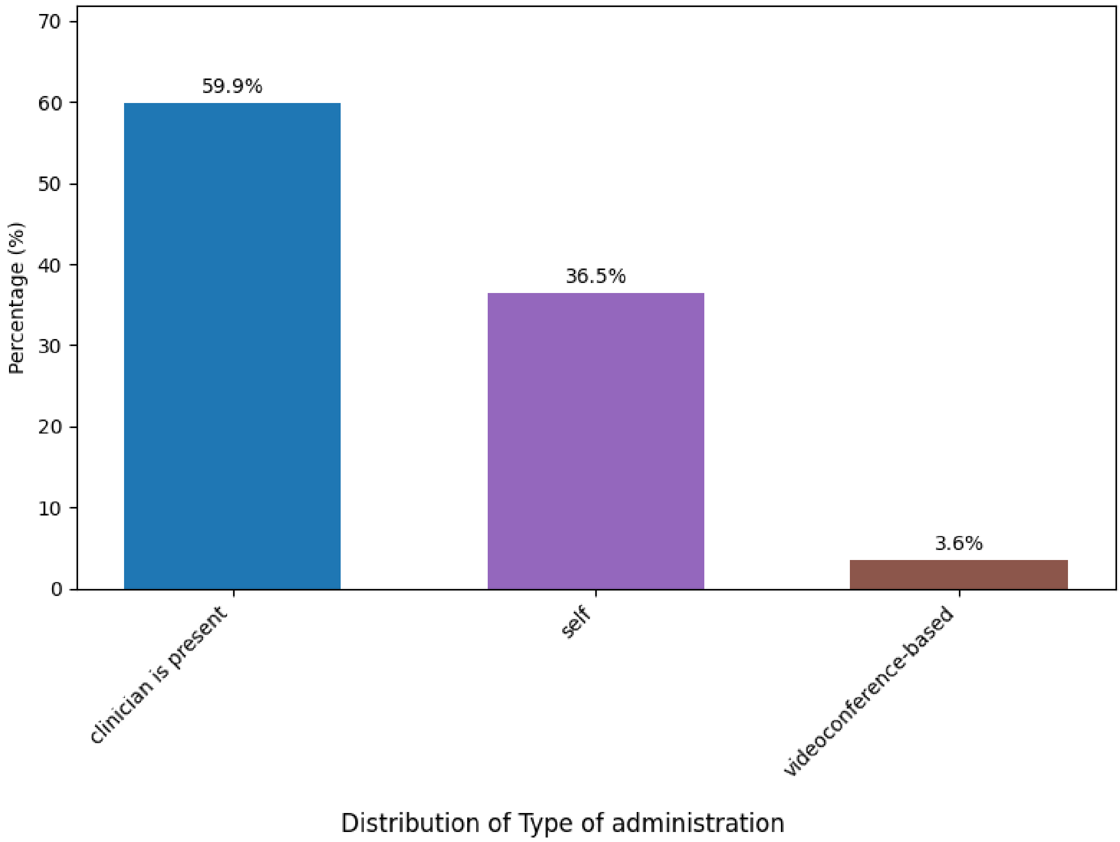
3.1. Overall results

Before presenting the results, it is important to address a few key methodological aspects. First, we conducted a comprehensive review of the literature related to the use of digital tools in assessments. This review included studies that employed a wide range of digital formats, such as tele-administration of traditional paper-and-pencil tests, computerised test batteries, and other innovative digital tools. Despite these categories differ significantly, we aimed at capturing the full spectrum of digital tools used in assessments, excluding only telephone-based assessments from our analysis. Second, we aimed to provide a general overview of the characteristics of all 252 included studies. The summary below highlights the salient features of the studies, with a particular focus on aspects related to accessibility. Following this general report, we adopted a more detailed approach, focusing specifically on the most frequently employed digital tools and those which resulted to be the most accessible.

3.1.1. Type of Administration

A total of 252 studies were included in the review. In 59.92% (n=151) of the studies, a clinician was present during the administration of digital tools. Self-administered tools were used in 36.51% (n=92) of studies, while 3.57% (n=9) focused on tele-based interventions consisting in synchronous videoconference-based assessment.

Figure 2 Frequency distribution of the type of administration.



3.1.2. Cognitive Functions Assessed

The vast majority of publications employed digital tools assessing both executive functions and attention, accounting for 80,08 % (n=201) of the studies. Studies assessing attention alone accounted for 13.15% (n=33), while those assessing executive functions (EF) alone were 6.77% (n=17).

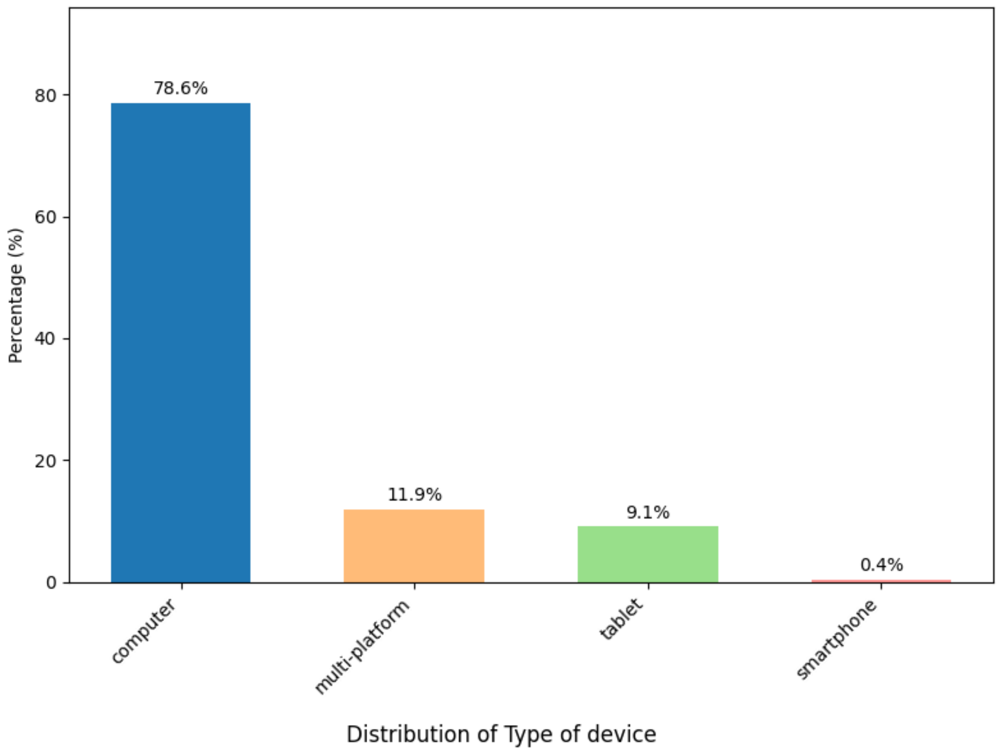
3.1.3. Type of Tool

Desktop-based tools were the most frequently used, appearing in 64.68% (n=163) of the studies. Web-based tools were present in 21.03% (n=53), followed by mobile applications (5.95%, n=15), hybrid tools, meaning tools incorporating different modalities (4.76%, n=12), and wearables (3.57%, n=9).

3.1.4. Type of Device

Computers were the dominant platform, utilised in 78.57% (n=198) of studies. Multi-platform devices were used in 11.90% (n=30), tablets in 9.13% (n=23), and smartphones in only 0.40% (n=1) of the studies.

Figure 3 Frequency distribution of the type of device.



3.1.5. Accessibility of Digital Tools

The accessibility of digital tools was predominantly limited, with 86.11% (n = 217) of studies utilizing tools that required restricted access, available only through the purchase of a commercial license and/or verification of legitimate use as academicians or health professionals. In contrast, 8.73% (n = 22) of studies employed platform-based tools that necessitated expensive and specialised equipment, while only 5.16% (n = 13) used freely accessible tools.

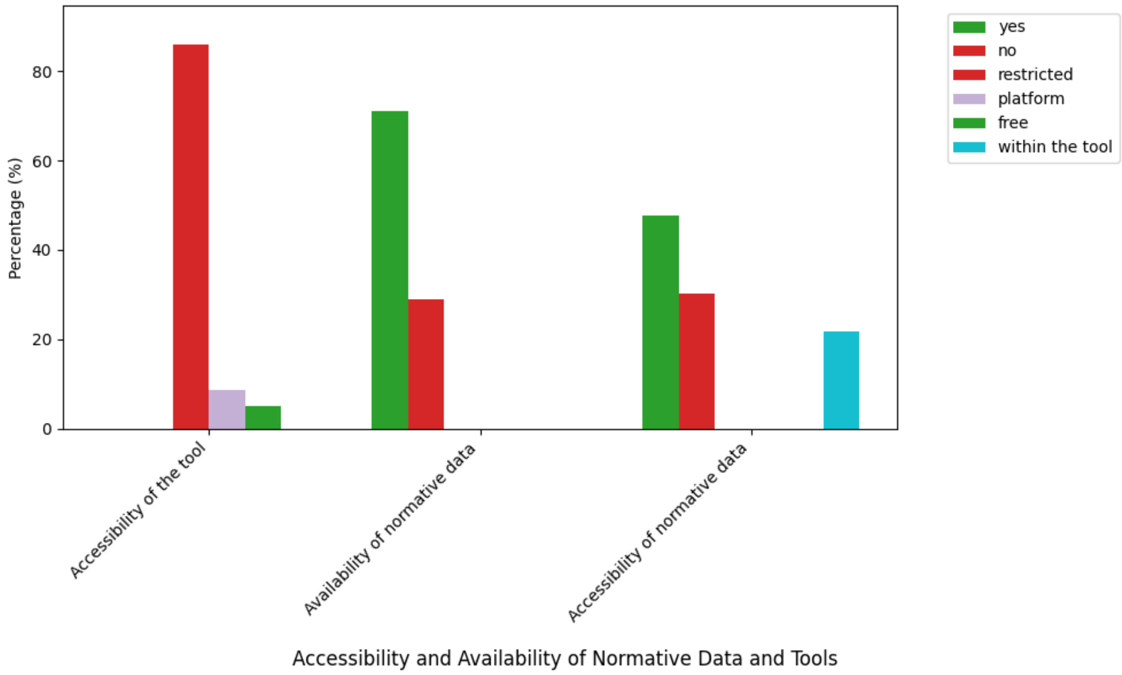
3.1.6. Availability of Normative Data

A significant portion of the studies, 71.03% (n = 179), reported the availability of normative data for the digital tools employed, whereas 28.97% (n = 73) utilised digital tools that lacked normative data.

3.1.7. Public Accessibility of Normative Data

Among the studies utilizing digital tools with existing normative data, 47.62% (n = 120) made the normative data publicly accessible, while 21.83% (n = 55) provided normative data within the tool itself, contingent upon the purchase of a commercial license. Additionally, 30.16% (n = 76) did not offer public access to the normative data, and none of the studies offered normative data upon request.

Figure 4 Frequency distributions representing the availability of normative data and the accessibility of the digital tools and their normative data.



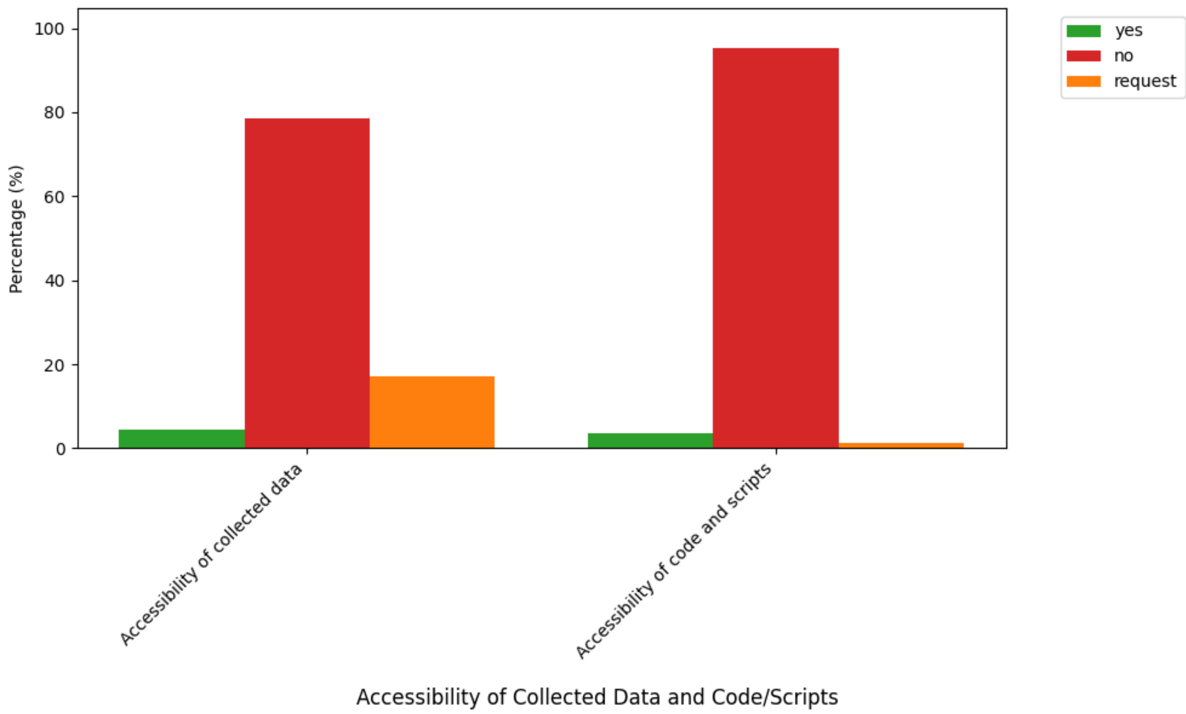
3.1.8. Availability of Collected Data

In 78.57% (n=198) of the studies, collected data was not available for access. However, 17.06% (n=43) allowed data access upon request, and 4.37% (n=11) provided full access to the data.

3.1.9. Availability of Scripts

The majority of the studies (95.24%, n=240) did not make their scripts available. Only 3.57% (n=9) made scripts publicly available, while 1.19% (n=3) provided access to scripts upon request.

Figure 5 Frequency distributions representing the accessibility of collected data and code/scripts.



3.1.10. Most Employed Digital Tools

Several digital tools were employed across multiple studies, with the most common being NeuroTrax (n=16) and Mindstreams (n=11), Cognitive Drug Research (CDR, n=19), Cambridge Neuropsychological Test Automated Battery (CANTAB, n=15), and Cogstate (n=11). Other tools included Automated Neuropsychological Assessment Metrics (ANAM, n=9), and Central Nervous System Vital Signs (CNS VS, n=8). Additionally, tools such as NIH Toolbox Cognitive Battery (n=4), Cognitron (n=4), Vienna Test System (n=3), and Iron Psychology (FePsy, n=3) were also utilised. Collectively (n=103), these tools accounted for 40.87% of the studies.

3.2. MOST AVAILABLE DIGITAL TOOLS: A CLOSER LOOK

All the most employed digital tools share significant similarities: they are all cognitive batteries assessing multiple cognitive domains for screening purposes, the majority can be self-administered, though normally, especially when the study population is a clinical one, a clinician or another professional is present to supervise the test, they are available in several languages, their access is restricted and conditioned upon purchase of a license, they consist in desktop software that can be downloaded and utilised on personal computers, they have been validated on a large sample with specific validation on clinical populations, normative data is publicly available, data and scripts are not available, they are widely employed in clinical settings to measure cognition in relationship to rehabilitation programs, interventions, physiological and neural correlates of pathological conditions. Table 1 summarizes the most relevant features of each of the most available digital tools.

NeuroTrax

The web-based *NeuroTrax Computerised Neuropsychological Battery*, which resulted to be the most commonly employed digital tool together with the Cognitive Drug Research, is a computerised neuropsychological battery assessing a wide range of cognitive domains (i.e., memory, executive function, attention, information processing speed, visuospatial perception, verbal function and motor skills). The tool is designed to be flexible, making it possible for different tests to be administered based on the specific needs of the study or clinical setting. Furthermore, it can be self-administered, without the need of a professional. The battery is a reliable and valid measurement and has been used previously in a wide variety of studies, both in clinical research (Bar-On Kalfon et al., 2016; Bergmann et al., 2023; Elkana, Adelson, et al., 2019; Elkana et al., 2021, 2022; Elkana, Falcofsky, et al., 2019; Golan et al., 2020; Hadanny et al., 2018; Jackson et al., 2023; Lutski et al., 2017; Mamikonyan et al., 2015; Natovich et al., 2016; Takeda et al., 2021; Tal et al., 2017; Weinstein et al., 2021) and in clinical practice to assess cognitive function in various populations, especially in individuals with neurological conditions such as multiple sclerosis (Bergmann et al., 2023; Golan et al., 2020; Jackson et al., 2023; Takeda et al., 2021), TBI (Hadanny et al., 2018; Tal et al., 2017), Parkinson's Disease (Mamikonyan et al., 2015), in psychiatric disorders (Elkana, Adelson, et al., 2019; Hamo et al., 2018), and in healthy aging populations (Hoth et al., 2008). Among its strengths, it provides immediate scoring and feedback, it can be administered either in-person or remotely and standardised norms are available based on age and educational level (Doniger et al., 2006; Dwolatzky et al., 2003; Schweiger et al., 2003). Furthermore, the NeuroTrax Battery is suitable and often used for longitudinal assessments, making it an excellent digital tool for tracking cognitive changes over time (Hadanny et al., 2018; Hoth et al., 2008; Lutski et al., 2017; Weinstein et al., 2021). The battery is available in English, Hebrew, Russian and Spanish, facilitating multi-centre cross-cultural studies. Importantly, normative data is publicly available and thoroughly discussed by Glen Doniger, director of Scientific Development at NeuroTrax Corporation (guide to normative data).

Before delving into the description of the Mindstreams Battery, it is important to mention that it was rebranded as NeuroTrax in the mid-2000s, thus constituting its legitimate predecessor. Initially, the cognitive assessment tools were marketed under the name Mindstreams, but as the company evolved and expanded its product offerings, the name was changed to NeuroTrax to reflect a broader focus on digital cognitive assessment and health technology. This rebranding aimed to unify the products and services under a single, recognizable name. Specific dates vary in different sources, but the transition occurred around 2006 or shortly thereafter.

Mindstreams

Mindstreams is a computerised battery designed primarily for clinical use and research to assess cognitive decline, especially in the context of mild cognitive impairment (Doniger et al., 2009; Dwolatzky et al., 2003; Osher et al., 2011) and early dementia (Doniger et al., 2005), neurodegenerative diseases like Alzheimer's (Dwolatzky et al., 2003; Gutman et al., 2016) and MS (Dreyer-Alster et al., 2022; Dwolatzky et al., 2003), post-stroke (Shopin et al., 2013), genetic conditions such as Fabry disease and Down syndrome (Elstein et al., 2012; Gutman et al., 2016; Thaler et al., 2012) and psychiatric conditions such as schizophrenia (Ritsner et al., 2006).

Differently from NeuroTrax, it is a hybrid tool, with custom software installed on a local desktop computer for running the interactive cognitive tests, while the web-based features are used for administrative purposes, such as secure entry and storage of demographic data and uploading test results to a central server for processing and report generation (Ritsner et al., 2006). Similarly to NeuroTrax, it includes tests for memory, executive function, attention, processing speed, and visuospatial skills. Tailored primarily for older adults and individuals at risk of cognitive impairment, it includes a comprehensive report after the assessment, which provides clinicians with actionable data for diagnosis or treatment planning. It has been validated in clinical settings (Dreyer-Alster et al., 2022; Dwolatzky et al., 2003, 2010; Elstein et al., 2012; Gutman et al., 2016; Osher et al., 2011; Ritsner et al., 2006; Shopin et al., 2013) and can help in early detection of cognitive decline, especially in elderly populations. It's user-friendly and can be self-administered or administered by a clinician. It provides an efficient, non-invasive way to assess cognitive health. Additionally, the platform offers adaptive testing, which adjusts to the respondent's performance to maximize accuracy. The data is compared against age-matched norms, helping in the early detection of cognitive impairment. In addition, different variants of the Mindstreams battery have been developed and validated, including the Mindstreams Global Assessment Battery (GAB)/Mindstreams Battery for Mild Impairment[5] (Doniger et al., 2005, 2009; Dwolatzky et al., 2003; Elstein et al., 2012; Osher et al., 2011; Shopin et al., 2013), the Mindstreams battery for Moderate Impairment (Dwolatzky et al., 2010) and the Mindstreams battery for Moderate to Severe Impairment (Gutman et al., 2016). The battery is available in English, Hebrew, Russian, Spanish and Arabic, facilitating multi-centre cross-cultural studies. Normative data is presented and discussed by Glen M. Doniger, PhD Director of Scientific Development (guide to normative data, Mindstreams).

Cognitive Drug Research

The CDR (Cognitive Drug Research) computerised assessment system has emerged as a widely utilised tool for neuropsychological testing, particularly in clinical trials, due to its ability to provide precise and reliable assessments of cognitive function. Initially developed by Professor Keith Wesnes in the late 1970s, the system was designed to enhance the objectivity and accuracy of cognitive testing by offering millisecond-level precision in measuring reaction times and accuracy. The system was originally administered via laptop computers in clinical environments, where participants responded

[5] the Mindstreams Battery for Mild Impairment was later renamed Mindstreams Global Assessment battery.

using a two-button response box. Over time, the CDR system has evolved to incorporate web-based administration, enabling participants to complete assessments remotely using keyboard inputs on their own devices, thereby expanding the system's reach and flexibility in clinical research.

The CDR system's validity and reliability are well-established across multiple cognitive domains, including attention, working memory, information processing, episodic memory, and executive function. The system's sensitivity in detecting even subtle changes in cognitive performance makes it particularly valuable in clinical trials aimed at assessing the cognitive effects of interventions in both healthy individuals (Downey et al., 2018) and clinical populations (Bucks et al., 2008; Kohli et al., 2009; Walker et al., 2000). One of the strengths of the CDR system is its capacity for repeated testing over time, with parallel forms available to mitigate learning effects, which is crucial for longitudinal studies. In this context, the CDR system facilitates the measurement of intervention-driven cognitive changes with minimal participant burden, thanks to its brief test durations (7 to 30 minutes) and user-friendly interface. The automated data capture and scoring eliminate the variability introduced by manual data entry, ensuring consistent data quality across testing sessions.

The evolution of the CDR system has also addressed the logistical challenges posed by traditional cognitive assessments. The web-based version retains the original millisecond accuracy while supporting more flexible administration in remote settings, making it possible to include participants who may not be able to attend in-clinic visits. This broadens the scope of clinical trials and ensures more inclusive research participation.

Additionally, the system benefits from an extensive normative database, developed over 35 years, which supports the interpretation of cognitive test findings across a wide range of areas. This industry-leading database is particularly valuable for comparative studies and allows for more robust cross-sectional and longitudinal analyses. Furthermore, the CDR system has been validated in over 50 languages, making it adaptable for cross-cultural research and extending its applicability in international clinical trials.

In terms of hardware, the system is compatible with laptops and can integrate with ancillary equipment for specialised cognitive tests, such as postural stability meters, flicker fusion devices, and joysticks. However, the internet-based version of the CDR system does not require additional equipment, relying instead on keyboard inputs, which further enhances its accessibility for remote use.

In conclusion, the CDR system has become a crucial tool in cognitive testing, combining precision, flexibility, and scalability. Its continuous development and the addition of web-based capabilities have further consolidated its role as one of the most widely validated and effective cognitive testing systems used in clinical trials today.

The CDR system is particularly valuable in repeated assessments over longitudinal clinical trials, where it is used to quantify intervention-driven cognitive changes in both healthy individuals (Kennedy et al., 2001; Komanduri et al., 2022; Moss et al., 2003; Wesnes et al., 2000) and patients with cognitive impairments (Dunbar et al., 2011; Ripley et al., 2014; Wesnes et al., 2005), related to different pathologies such as attention deficit and hyperactivity disorder (ADHD) (Wilens et al., 2008) TBI (Ripley et al., 2014), dementia with Lewy bodies (McKeith et al., 2000; Watson et al., 2017) and Parkinson's disease (Fernandez et al., 2023; Firbank et al., 2017; Wesnes et al., 2005). Its capacity to reliably track cognitive shifts over time, combined with its user-friendly interface and scalability, makes it an indispensable tool for both clinical research and clinical practice. As the system continues to evolve and undergo validation, it remains at the forefront of computerised cognitive testing, delivering robust data collection with minimal error, thus ensuring high-quality and consistent results across various studies. Finally, normative data is publicly available (Wesnes et al., 2016).

CANTAB

The CANTAB (Cambridge Neuropsychological Test Automated Battery) is a widely recognised computerised cognitive assessment tool initially developed as a desktop-based software. Over time, it has expanded to include web-based options such as CANTAB Connect, allowing remote administration on various devices, including tablets and computers, enhancing its scalability and flexibility (Backx et al., 2020). Depending on the specific version and mode of administration, CANTAB is now available as both a desktop and web-based tool, thus being adaptable for different research contexts and clinical environments.

CANTAB assesses a broad range of cognitive domains, including memory, executive function, attention, and processing speed, and has demonstrated high sensitivity and precision across numerous clinical and research studies. The tool is available in multiple languages (English, Spanish, French, Lithuanian, Polish, Dutch, and Hebrew), which facilitates its use in cross-cultural research, enhancing its accessibility for global studies.

One of CANTAB's strengths lies in its highly validated, scientifically grounded approach. The battery includes language-independent tasks, making it ideal for international studies, and offers multiple task variants that prevent floor and ceiling effects. This flexibility enables researchers to tailor assessments to various populations, from healthy individuals to those with cognitive impairments, including conditions like TBI (Hart et al., 2017), mild cognitive impairment (Israsena et al., 2021), post-stroke recovery (Campbell et al., 2023), schizophrenia (Braw et al., 2008; Ritsner et al., 2006), Alzheimer's disease (Kuzmickienė & Kaubrys, 2016), Parkinson’s disease (Firbank et al., 2017) and multiple sclerosis (Cotter et al., 2018). Importantly, the cognitive assessment provided by CANTAB is often employed in studies measuring brain activity with neuroimaging techniques such as magnetic resonance imaging and electroencephalography, thus facilitating the identification of neurocognitive markers (Firbank et al., 2017; Hart et al., 2017; Israsena et al., 2021; Qian et al., 2022).

By utilizing parallel modes and stimuli randomization, CANTAB is designed to minimize practice effects. Its automated data capture and scoring further enhance the accuracy and consistency of results, reducing the possibility of errors. Additionally, its remote accessibility makes it possible for participants to complete assessments from any location, using their own devices, thus constituting a highly inclusive and scalable solution for cognitive testing. The engaging and user-friendly interface of the battery, combined with clear instructions, ensures high adherence to tasks, whether administered in-clinic or remotely. Finally, normative data is publicly available (Abbott et al., 2019; Wurr, 2023).

Cogstate

The web-based computerised battery Cogstate is a widely used digital tool for neuropsychological assessment, designed to offer scientifically validated and operationally efficient tests that are well-suited for both clinical trials and research settings. Cogstate assessments are optimised for repeated administration, showing minimal practice or learning effects, making them highly reliable for longitudinal studies. These tests can be administered in a variety of settings, including sites with limited cognitive testing experience, and are designed to fit into tight protocol schedules, ensuring they are brief and easy to integrate into clinical workflows.

One of the distinctive features of the Cogstate system is its use of novel stimuli, which makes the tests culture-neutral and independent of participants' educational background, making sure that assessments provide accurate data across diverse populations.

The Cogstate battery includes a range of cognitive tests that target specific cognitive domains, such as memory, psychomotor function, attention, executive function, and working memory. Examples include the Groton Maze Learning Test (GMLT) for executive function, the One Back Test (ONB) for working memory, and the International Shopping List Test (ISLT) for verbal learning. These tests can be customised and grouped together based on the unique requirements of the study design and population being assessed. Furthermore, the battery is available in 43 different languages, thus being an excellent candidate for cross-cultural studies.

An important consideration for researchers and clinical neuropsychologists using Cogstate is that while normative data exist for the battery, these data are only available within the tool itself and are not publicly accessible. This limits external validation but guarantees that the data are tightly controlled and consistently applied across studies.

In terms of administration, the Cogstate battery is effective whether conducted on-site in a clinical setting or remotely, showing flexibility in how and where cognitive data can be collected. This remote capability is especially useful for decentralised clinical trials, where participants may not have easy access to clinical sites. Additionally, the system complies with regulatory standards such as 21 CFR Part 11 and meets Good Clinical Practice (GCP) guidelines, certifying the security and integrity of the data collected during clinical trials.

Its most common applications can be found in studies involving neurological and psychiatric conditions such as multiple sclerosis (Charvet et al., 2018; Eilam-Stock et al., 2021), Alzheimer's disease (Mielke et al., 2014), schizophrenia and mild TBI (Maruff et al., 2009). It is often used to detect early cognitive markers and track changes over time, particularly in relation to disease progression (Cumming et al., 2012; Eilam-Stock et al., 2021; Mielke et al., 2016) or treatment effects (Charvet et al., 2018). The battery is also extensively used in research focusing on cognitive impairment due to factors such as substance use (Cairney et al., 2007), acute medical conditions like stroke (Cumming et al., 2012) and chronic conditions such as complex congenital heart disease (Verrall et al., 2024) . Its ability to provide quick, reliable assessments with minimal learning effects makes it an ideal tool for longitudinal studies and clinical trials, whether in on-site or remote settings.

Furthermore, the Cogstate battery has been validated against standard cognitive measures like the WAIS-IV (Kataja et al., 2017), confirming its sensitivity and reliability across a range of conditions, including dementia (Hammers et al., 2012), AIDS dementia complex (Maruff et al., 2009), and cognitive profiles in healthy older adults (Veal et al., 2023). Overall, the Cogstate system is a versatile, reliable, and efficient tool for assessing cognitive function across a broad spectrum of populations and settings, making it highly valuable for clinical trials and neuropsychological research. Its ability to detect subtle cognitive changes and its adherence to rigorous regulatory standards further underscore its relevance in modern cognitive testing.

Automated Neuropsychological Assessment Metrics (ANAM)

The Automated Neuropsychological Assessment Metrics (ANAM) is a well-established computer-based cognitive assessment tool, originally developed by the U.S. Department of Defense to evaluate cognitive function in military personnel. Over time, ANAM has become widely used in both clinical and research settings, demonstrating its versatility across different populations and conditions. ANAM assesses a broad range of cognitive domains, including attention, concentration, reaction time, memory, processing speed, and decision-making. This adaptability makes it highly suitable for tracking cognitive changes over time, especially in longitudinal studies.

The design and components of the battery reflect contributions from various scientists and have been refined over decades. The system comprises 22 neurocognitive tests, which can be tailored into customised batteries based on the needs of a specific study or clinical assessment. These tests are administered via desktop-based software, typically installed on computers in clinical or research environments. While primarily used for in-person testing, ANAM has also been adapted for remote applications, although it is not currently optimised for tablets or web-based use. The system provides researchers and clinicians with the ability to assess and monitor cognitive performance through repeated testing, offering tools for data extraction, statistical reporting, and performance comparisons to track an individual's cognitive status over time.

The validity and reliability of the ANAM battery are well-documented, particularly in military settings where it has been extensively used to study the effects of TBI, sports concussions, and the cognitive impacts of military deployment. In fact, ANAM has been referenced in over 300 peer-reviewed studies, solidifying its place as a reliable method for detecting subtle cognitive changes. ANAM’s tests have been widely accepted for their sensitivity to cognitive fluctuations in clinical populations, including those with systemic lupus erythematosus (SLE) (Hanly et al., 2012; Petri et al., 2008; Roebuck-spencer et al., 2006; Teo et al., 2020), where cognitive function is often compromised by the disease or its treatments.

The flexibility of the ANAM battery extends beyond clinical use, having been applied in studies of cognitive impairment in conditions like chronic rhinosinusitis (Soler et al., 2015) and in trials evaluating cognitive changes associated with migraine treatments, such as the use of sumatriptan (Farmer et al., 2001). Its application in the military (Vincent, Roebuck-Spencer, Lopez, et al., 2012) is particularly comprehensive, where it has been used in sports concussion studies at institutions like West Point and in TBI research during training at Ft. Bragg. The tool has also been employed by major organizations such as NASA, which utilizes ANAM-based tests to assess cognitive function in astronauts, further showcasing its broad applicability across high-stakes environments.

ANAM's modularity allows for assessments to be customised based on the specific needs of the study, whether assessing executive function, working memory, or reaction times. Its tests have proven particularly effective in tracking cognitive changes in patients with neurological impairments or exposure to risk factors. The extensive normative database of the tool (Vincent, Roebuck-Spencer, Gilliland, et al., 2012) supports its ability to compare individual performance against large population data, ensuring precise and meaningful interpretations of cognitive function over time.

In research involving virtual reality tasks, such as the Virtual Reality Stroop Task (VRST) used to assess attentional processing in military personnel (Parsons et al., 2013), ANAM has been shown to integrate with modern assessment technologies (Armstrong et al., 2013). This further demonstrates its capacity to evolve alongside advancements in cognitive testing tools. Importantly, the tool is available in multiple languages, ensuring its usability in cross-cultural studies, although the specific languages supported depend on the context of the study.

In conclusion, ANAM is a robust, reliable, and scientifically validated tool for neuropsychological assessment. Its use in longitudinal research, clinical trials, and military testing highlights its ability to track cognitive changes across various populations and conditions. Its desktop-based software provides the infrastructure for repeated testing, customizability, and effective data analysis, making it a valuable resource in both clinical practice and research studies.

Central Nervous System Vital Signs (CNSVS)

The CNS Vital Signs assessment platform is a versatile computerised neurocognitive testing tool widely employed in both clinical practice and research settings. Originally designed to assess a wide range of cognitive and behavioural functions, it has proven to be a reliable and valid tool for detecting and tracking cognitive impairments. The platform allows for both in-office and remote administration, making it suitable for various clinical environments and large-scale research projects. Its user-friendly design and straightforward hardware requirements, such as compatibility with Windows-based desktop and laptop computers, make it an accessible tool for clinicians and researchers alike. CNS Vital Signs also offers web-based administration, enhancing its flexibility and usability in remote or decentralised studies.

The system supports over 50 languages, ensuring its applicability in cross-cultural studies and multinational trials, while maintaining high levels of validity and reliability. This wide language availability enables CNS Vital Signs to deliver culturally neutral assessments across diverse populations. Its sensitivity to neurocognitive changes is one of its major strengths, with the ability to detect subtle impairments that may not be evident through standard assessment techniques. This makes CNS Vital Signs particularly valuable for neurocognitive deficits related to conditions such as multiple sclerosis (Papathanasiou et al., 2014, 2017), Alzheimer's disease, and cancers (Collins et al., 2018; Rydelius et al., 2020).

CNS Vital Signs yields millisecond precision in tracking cognitive performance, particularly in domains such as attention, processing speed, executive function, and memory. This precise measurement capability is crucial for monitoring the progression of diseases and assessing the efficacy of therapeutic interventions or medications. In clinical trials, the system has been widely used to evaluate the cognitive effects of pharmaceutical treatments, aiding in early identification of treatment responses or adverse effects. Its capacity for longitudinal tracking (Rydelius et al., 2020) is particularly advantageous for research studies focused on cognitive function over time.

Furthermore, the modularity of the CNSVS system supports the customization of test batteries based on specific research or clinical requirements. This flexibility is further enhanced by the availability of real-time data reporting, enabling researchers to monitor cognitive outcomes throughout the trial. Moreover, CNS Vital Signs ensures compliance with HIPAA and 21 CFR Part 11 standards, safeguarding the secure management of patient data in both clinical and research environments.

Researchers have extensively used CNS Vital Signs in studies evaluating postmenopausal cognitive function (Bojar, Owoc, Gujski, et al., 2015; Bojar, Owoc, Wojcik-Fatla, et al., 2015; Gujski et al., 2017) and the cognitive impacts of chronic obstructive pulmonary disease (COPD) (Campman et al., 2017). The use of the platform in such varied contexts demonstrates its applicability across a broad spectrum of cognitive and behavioural health domains. Its role in clinical practice is equally important, with clinicians utilizing the tool to establish baseline cognitive function and track changes over time in patients with neurodegenerative disorders, TBI, and psychiatric conditions.

Overall, CNS Vital Signs stands out as a reliable, valid, and flexible neurocognitive assessment platform, providing clinicians and researchers with the tools needed to assess and track cognitive function across diverse populations and settings. Its ability to detect subtle cognitive impairments, coupled with its ease of use and adaptability, makes it a valuable tool in both clinical and research applications, particularly for longitudinal cognitive studies and clinical trials involving complex neurocognitive disorders. Finally, normative data is publicly available (Rijnen et al., 2020).

NIH Toolbox Cognitive Battery

The NIH Toolbox is a digital neurocognitive assessment platform designed to evaluate a wide range of cognitive, motor, sensory, and emotional functions across the lifespan, from age 3 to 85 and older. The system provides a comprehensive suite of valid and reliable tests, widely used in both clinical practice and research settings and offers clinicians, researchers, and academicians the possibility to assess cognitive and behavioural performance efficiently. The NIH Toolbox has been employed in numerous studies to track cognitive aging, assess neurological conditions, and evaluate cognitive performance in both healthy and clinical populations.

The platform is primarily available through an iPad app, which users can download from Apple App Store. This means it is exclusively supported on iPads, making it a mobile, tablet-based tool. The system is designed to be self-administered with guidance from the app, thus requiring minimal involvement from the clinician, but can also be used in clinical settings with supervision, providing flexibility in different research and clinical contexts. The languages available for the NIH Toolbox include English, Spanish, Hebrew, and Arabic, with additional translations in progress, making it suitable for cross-cultural research and international clinical trials.

In terms of validity and reliability, the NIH Toolbox has been rigorously tested and validated across various populations and settings. Validation studies have compared its performance with gold standard neuropsychological assessments, demonstrating its ability to produce reliable results that correlate well with traditional cognitive testing (Ott et al., 2022). For example, studies such as those examining the relationship between cognitive aging and hippocampal volume in older adults (O'Shea et al., 2016) employed the NIH Toolbox, validating the its sensitivity to detecting subtle cognitive decline. Additional studies, like those on Covid-19 long haulers (Graham et al., 2021) and individuals with genetic diseases such as phenylketonuria (Christ et al., 2023), further confirm its efficacy in assessing cognitive dysfunction in specific clinical populations.

The NIH Toolbox is particularly useful for assessing multiple domains of cognitive function, including working memory, executive function, attention, and processing speed. It offers composite scores, such as the Fluid Cognition Composite and Crystallised Cognition Composite, which provide a broad view of an individual's cognitive abilities. Its ability to track cognitive changes longitudinally is a significant benefit in research and clinical practice, where ongoing monitoring is often required to assess disease progression, treatment effects, or normal aging. Normative data is publicly available (Casaletto et al., 2015).

Cognitron

The Cognitron platform is a state-of-the-art web-based cognitive assessment tool designed for remote administration on web browsers and mobile applications. It is highly flexible, allowing for the assessment of cognition and mental health across large-scale and longitudinal studies. The tool is specifically built to run online without requiring supervision, making it cost-effective and easy to use for remote cognitive testing on home computers, smartphones, and tablets.

Cognitron supports over 100 scientifically validated cognitive tasks that have been demonstrated to be highly sensitive to cognitive differences, including subtle changes associated with the early and prodromal stages of neurological conditions. Its sensitivity surpasses that of many traditional, supervised cognitive assessment scales, making it an effective tool for identifying cognitive impairments in clinical populations such as TBI (Giovane et al., 2023), Parkinson's disease (Bălăeţ et al., 2024), and COVID-19 patients (Hampshire et al., 2022). Studies have shown that Cognitron is capable of detecting cognitive deficits linked to conditions such as hippocampal atrophy in autoimmune limbic encephalitis (Shibata et al., 2024), validating its use in complex neuropsychological conditions.

The platform is highly customizable, with the ability to configure specific assessment batteries for particular studies or clinical needs. It supports multiple languages, making it accessible for international research and healthcare applications. Additionally, it can seamlessly integrate into healthcare data systems, enabling real-time transmission of diagnostic reports and participant feedback, which enhances its utility in both research and clinical practice.

Its reliability is backed by its use in over 500,000 assessments globally, with extensive validation studies supporting its accuracy across different populations. Normative data is available within the tool.

Vienna Test System

The Vienna Test System (VTS) is a highly flexible and versatile digital tool designed for a wide range of psychological assessments, including cognitive, personality, and clinical neuropsychological testing. It can be administered either online or offline, offering users the ability to choose between web-based access or locally installed desktop software.

The VTS can be run on desktop and laptop computers, providing users with secure testing options whether the respondent is on-site or participating remotely. For remote administration, VTS supports multiple formats, including an open mode, where a test link is sent to respondents, and a proctored mode, which integrates a video call for added security and supervision during testing. This variety of administration formats ensures that the system can be adapted to specific study or clinical requirements, whether in a supervised or unsupervised context. The system also supports group testing, further extending its utility in research environments that require large-scale data collection.

One of the strengths of the Vienna Test System is its wide language support, offering tests in numerous languages, making it ideal for international and cross-cultural research. This feature ensures fair testing across diverse populations, supported by the comprehensive norms, which provide up-to-date representative samples. Users can select appropriate norms based on factors such as age, gender, and education level, ensuring meaningful comparisons and precise interpretations of test results. Additionally, VTS allows the import of custom norms for specific contexts, such as comparing respondents to professionals in particular fields like aviation or sports.

The validity and reliability of the Vienna Test System are well-established, backed by decades of research and widespread use in clinical and academic settings. Its psychometric properties are continually validated, and its ability to detect subtle differences in cognitive performance has been shown to surpass traditional clinical scales, as illustrated in studies assessing fitness-to-drive (Tinella, Caffò, et al., 2021; Tinella, Lopez, et al., 2021) and the detection of ADHD feigning behaviours (Fuermaier et al., 2018).

The VTS also integrates seamlessly with a variety of input and output devices designed to measure psychomotor skills, such as fine motor coordination and sensorimotor processes. These proprietary devices allow for the assessment of more complex cognitive functions that involve both cognitive processing and motor responses, adding an additional layer of precision in testing. For example, the system can be used to test eye-hand coordination and peripheral perception, expanding the range of psychological and physiological functions that can be assessed.

Automatic scoring and error-free result generation are key features of the VTS; results are instantly available after testing, and the system offers users the ability to export data to software like Excel or SPSS for further analysis. Integration with healthcare data systems is also possible through the Vienna Test System Integration Service, enabling seamless data sharing between the test system and other clinical software.

In terms of employment, the Vienna Test System is commonly used in clinical settings for neuropsychological assessments, such as evaluating fitness to drive (Tinella, Caffò, et al., 2021; Tinella, Lopez, et al., 2021) and cognitive efficiency across different age groups.

Iron Psychology (FePsy)

Fepsy is a comprehensive, menu-driven software designed for automated psychological testing and cognitive assessment. It is primarily used in research and clinical settings for neuropsychological evaluations and can be run on Microsoft Windows operating systems (Windows 7 to Windows 11). Fepsy supports both desktop software and touchscreen interfaces, enabling patients to interact with the system through a mouse or touchscreen depending on the test requirements. This flexibility in input methods makes it accessible to a wide range of users, including those with limited motor abilities.

The Fepsy system is available in 21 languages, including most European languages such as English, Dutch, German, French, Spanish, Italian, and Russian, among others. This wide language support makes it suitable for use in international studies and multicultural clinical environments, ensuring fair and consistent testing across different populations.

One of its significant features is its reliable database system, which stores all test results permanently. This allows for longitudinal tracking of cognitive performance, and the system is capable of recognizing patients who have been tested before, supporting easy comparison of previous test results. Additionally, the results can be exported in ASCII format for further analysis in statistical programs such as SPSS or MS-Access, making the system highly compatible with research data analysis workflows. Fepsy also supports normative data gathered across various age groups, enhancing its utility in comparing individual performance to established norms.

The validity and reliability of Fepsy have been established through its use in a variety of clinical and research settings, including studies investigating memory performance and the effects of antiretroviral therapy on cognitive functions in HIV-positive patients (Obiabo et al., 2012; Odiase et al., 2007) and cognitive performance in epilepsy (Sunmonu et al., 2008). Its ability to capture fine-grained data such as reaction time and motor responses makes it particularly effective in detecting subtle cognitive impairments across a variety of neurological conditions. Fepsy has also proven to be a valuable tool in multinational studies and multi-centered research projects assessing the side effects of drugs on cognitive performance.

The system also offers integration with EEG devices, providing a simultaneous connection that allows for synchronised cognitive testing and EEG recording. This feature enhances its application in clinical neuropsychology and cognitive neuroscience, where it can be used to study the relationships between cognitive function and brain activity. The EEG integration is facilitated via serial or parallel port connections, and the system supports generating ASCII output for further analysis of EEG data in conjunction with cognitive test results.

Name	*Number of studies*	*Administration*	*Type*	*Device*	*Cognitive domains*	*Accessibility of the tool*	*Other accessibilities*	*Administration time*	*number of tasks*	*Italian*
NeuroTrax (Hanna-Pladdy et al., 2010)	16	self-administered	web-based	computer	attention, executive functions, information processing speed, memory, motor skills and visuospatial perception, verbal function	restricted	normative data	50 minutes	8 to 12	no
Mindstreams (Dwolatzky et al., 2004)	11	self-administered	desktop software	computer	attention, executive functions, memory, processing speed, and visuospatial skills	restricted	normative data	50 minutes	8 to 12	no
CANTAB (Robbins et al., 2010)	15	self-administered	desktop software	computer, tablet	attention, executive functions, emotion and social cognition, memory, psychomotor speed, memory	restricted	normative data	30 to 90 minutes	25	yes
COGDRAS (Simpson et al., 1991)	19	self-administered	desktop software	computer	attention, executive functions, information processing and episodic memory	restricted	normative data	7 to 30 minutes	8	no
Cogstate (Falleti et al., 2006)	11	self-administered	web-based	computer	attention, executive functions, memory and working memory, psychomotor function	restricted	none	15 to 20 minutes	4 (Brief Battery), >10	yes
ANAM (Kabat et al., 2001)	9	in person	desktop software	computer: integration with VR is common	attention, executive functions, concentration, decision-making, memory, processing speed	restricted	normative data	20 to 30 minutes	22	no
CNSVS (Gualtieri & Johnson, 2006)	8	self- and tele-administered	hybrid; both desktop software and web-based	computer	attention, executive functions, simple visual attention, composite memory, verbal memory, visual memory, processing speed, psychomotor speed, reaction time, and motor speed	restricted	normative data, 5 free trials	30 to 45 minutes	7	no
NIH (Gershon et al., 2010)	4	self-administered	mobile app	iPad	attention, executive functions, episodic memory, language, processing speed	platform and equipment-specific access	normative data, raw data	45 to 60 minutes	>50	no
Cognitron (Hampshire et al., 2021)	4	self-administered	web-based	multi-platform	attention (visuo-spatial), executive functions, semantic reasoning, spatial short-term memory, semantic memory, emotion recognition	free and open access	normative data (only within the tool), raw data	30 to 60 minutes	>100	no
Vienna Test System (Ong, 2015)	3	self- and tele-administered	hybrid; both desktop and web-based	computer	attention, executive functions, episodic memory, motor speed, reaction speed	restricted	normative data (only within the tool), raw data, demo version	1-2 hours	>120	yes
FePsy (Odiase et al., 2007)	3	in person	desktop software	computer; supports touchscreen	attention, executive functions, memory, motor and perceptual function	restricted	normative data (only within the tool)	30 to 60 minutes	11 (24 subtests)	yes

Table 1. *Summary table presenting the most salient features of the most employed digital tools for the neuropsychological assessment of attentive and executive functions*

3.3. MOST ACCESSIBLE DIGITAL TOOLS: A CLOSER LOOK

While availability refers to the existence of services, accessibility includes many components, such as the possibility to make use of various aspects of digital tools, for instance having access to normative data, collected data, raw or standardised, code and scripts used to run the tasks or perform statistical analyses on the data itself. The results of the assessment of the accessibility of the digital tools presented in the selected publications show that only 13 publications implemented digital tools available for free and open source, only 11 made the collected data available and only 9 shared scripts and source code.

When considering the number of publications presenting digital tools satisfying multiple conditions at the same time following a conjunction logic, only 5 publications (Bieri et al., 2014; Fiabane et al., 2023; Rute-Pérez et al., 2014; Scarpina et al., 2021; Steinke et al., 2021) presented digital tools which are both free and come with available scripts/source code, only 2 publications present digital tools which are both free and open source and share the collected data (Hampshire et al., 2022; Steinke et al., 2021) and only 1 publication (Steinke et al., 2021) fulfilled all these criteria altogether presenting a free open source digital tool, collected data and scripts. Following instead a more permissive inclusive disjunction logic, thus considering publications presenting digital tools fulfilling at least one of the aforementioned criteria 24 publications presented digital tools with at least one of those features (Bălăeţ et al., 2024; Bieri et al., 2014; Caffey & Dalecki, 2021; Demeyere et al., 2021; Fiabane et al., 2023; Foerster et al., 2019; Foxe et al., 2024; Gamito et al., 2016; Giovane et al., 2023; Hampshire et al., 2022; Jaffe et al., 2022; Junghaenel et al., 2023; Ott et al., 2022; Rute-Pérez et al., 2014; Scarpina et al., 2021;

Shibaoka et al., 2023; Shibata et al., 2024; Steinke et al., 2021; Takaoka et al., 2024; Tinella, Caffò, et al., 2021; Travica et al., 2020; Troyer et al., 2014; Xu & Xian, 2023). Table 2 summarizes the most relevant features of the most accessible digital tools.

The study by (Steinke et al., 2021) examines the split-half reliability of a computerised version of the WCST, a widely recognised tool for assessing executive functions. The task was programmed using OpenSesame, a popular software platform for creating surveys and experimental stimuli. In addition to sharing the scripts and procedures of the task, the authors also provided the raw data collected during the study. This transparent, open-access approach not only facilitates the replication of studies but also enables researchers to modify the original task into numerous variants. Furthermore, it supports the development and distribution of free, open source, self-administered digital tools for assessing executive functions. Raw data, including number of errors and response times, are publicly available (cWCST_data).

Moving to the other studies presenting free and open source tools, the novel Bern Cognitive Screening Test (BCST) for assessing driving-relevant cognitive functions was designed by Bieri and colleagues (2014), focusing on skills like visuospatial attention, executive function, and eye-hand coordination and comparing the performance in the computerised battery with the performance in paper and pencil cognitive screening tests and the performance in the driving simulator testing of 41 safe drivers (without crash history) and 14 unsafe drivers (with crash history), showing that BCST is more accurate than paper and pencil screening tests, and better tolerated than driving simulator testing when assessing driving-relevant cognition in older drivers, emerging as a promising accessible and sensitive tool for the assessment of attentive functions with a heavy impact on daily-life activities such as driving. Similarly, (Rute-Pérez et al., 2014) discussed the challenges of cognitive evaluation and stimulation in elderly populations with cognitive impairment, emphasizing the potential of self-administered tools like the PESCO program, a computerised assessment and rehabilitation tool assessing attention, memory, reasoning and planning. Despite taking usability guidelines into account, the concurrent validity between PESCO and standardised tests resulted only to be moderate, suggesting the need and room for improvement.

Furthermore, Giovane et al. (2023) assessed the feasibility of the previously discussed Cognitron computerised battery in patients with TBI. This platform was also used in cognitive monitoring for Parkinson's disease patients (Bălăeţ et al., 2024), COVID-19 hospitalised patients (Hampshire et al., 2022) and autoimmune limbic encephalitis (Shibata et al., 2024). These studies demonstrate the potential of web-based tools in clinical settings, offering an accessible way to assess multiple cognitive domains across diverse patient groups. Furthermore, (Troyer et al., 2014) designed an on-line tool for the screening of cognitive deficits in healthy older adults: the Cogniciti platform, a newly self-administered, web-based digital tool assessing spatial working memory, divided attention, episodic memory and shifting. The final tasks were programmed in ASP.NET, JavaScript, and Adobe Flash, and the program was hosted on the Microsoft Azure cloud computing platform. Tasks could be completed from PC or Macintosh desk-top and laptop computers, but not from tablet computers or mobile devices. The study by Hampshire and colleagues (2022) shares demographic and raw behavioural (including reaction times) data (data_download), whereas the other aforementioned studies provide data upon reasonable request to the authors.

In their 2021 study, (Scarpina et al., 2021) investigated cognitive performance differences between younger and older adults using the Psychology Experiment Building Language (PEBL) test battery. The study assessed several cognitive domains, including selective attention, verbal and visuo-spatial short-term memory, inhibition, planning, problem-solving, and cognitive flexibility. Consistent with age-related cognitive decline, older adults exhibited poorer performance across these tasks compared to younger adults. Notably, familiarity with technology did not significantly affect performance outcomes, highlighting the utility of the PEBL battery for assessing cognitive function in older adults, regardless of their technological experience. In a related context Fiabane and colleagues (2023) explored cognitive recovery among early abstinent alcohol-dependent individuals following a residential rehabilitation program. Using the PEBL test battery to assess attentional capabilities and reasoning, the study found spontaneous improvements in certain cognitive functions, such as problem-solving (Tower of London) and cognitive flexibility (TMT). Both studies demonstrate the versatility of the PEBL test battery in assessing cognitive function across different populations—older adults and individuals with Alcohol Use Disorder (AUD).

PEBL, an open-source software platform, allows researchers to design custom experiments or use pre-built ones without licensing fees. It supports cross-platform compatibility across Windows, Linux, and macOS, using a user-friendly programming language that does not require knowledge of C++. This flexibility makes PEBL a valuable tool for cognitive research in diverse populations and settings. The ongoing collection of normative data would further enhance its applicability for digital cognitive assessments.

Other relevant studies include the work by Shibaoka and colleagues (2023), who introduced a brief, computerised cognitive assessment battery to investigate the associations between work performance and cognitive functioning. The digital tool, THINC-it®, is available for use on personal computers and touch screen tablet devices. The platform has been validated and is widely used for assessing cognitive function in patients with mood disorders and has been translated into multiple languages, including Japanese, and can be downloaded for free. Completing all THINC-it® components takes 10–20 min, and the task instructions are designed to minimize administrative requirements. The tool can be download from the website.

Notably, a VR-based assessment tool evaluating attention and memory in an highly ecologically valid fashion is the Systemic Lisbon Battery (SLB) (Gamito et al., 2016). The SLB, built on Unity 2.5, simulates a small city with various daily life environments like a house, supermarket, art gallery, pharmacy, and casino and requires participants to perform a short-term memory fruit-matching game, a working memory and attention task in a supermarket, and an attention task in an art gallery. While performance data for each task is automatically recorded and exported to Excel for analysis, the platform is continuously updated to expand task variety. Importantly, normative data is established and presented within the study.

Finally, the Box Task (Foxe et al., 2024) is a free, computerised visuospatial working memory task where participants search for hidden objects in boxes. Compatible with tablets and touch-screen laptops, it includes a developer's mode for customizing stimuli (Kessels & Postma, 2018). Written in Microsoft Visual Basic, it runs on all current Windows versions with minimal CPU requirements. The task involves increasing numbers of boxes (4, 6, 8) and tracks two error types: between-search (revisiting boxes with found objects) and within-search (revisiting empty boxes). A Levenshtein edit distance score measures search strategy efficiency, thus providing additional valuable information a traditional paper-and-pencil test could not offer. The task is presented with normative data.

Taken together, these digital tools represent a promising horizon in the development and adoption of accessible, valid, reliable, and sensitive methods for evaluating attention and executive functions. However, their widespread use is hindered by the limited availability of normative data and insufficient validation across diverse populations. These challenges, along with other important considerations, will be discussed in greater detail in the following section.

Name	*Number of studies*	*Administration*	*Type*	*Device*	*Cognitive domains*	*Software*	*Accessibilities*	*Administration time*	*Number of tasks*	*Italian*	*Specifics*
cWCST (Steinke et al., 2021)	6 (different versions, only 1 is freely accessible)	self-administered	desktop software	computer	executive functions (cognitive flexibility)	OpenSesame	raw data, scripts and procedures (cWCST_data&scripts); normative data is available for the original paper-and-pencil version	12-20 min	1	yes	
BERN (Nef et al., 2013)	1	in person	desktop software	computer	selective and divided attention, executive function, eye-hand coordination, distance judgment, and speed regulation	MATLAB	free for download	15 min	5	no	commercially available steering-wheel and custom-designed foot-pedal
PESCO (Rute-Pérez et al., 2014)	1	self-administered	desktop software	computer	attention, memory, executive functions (reasoning and planning)	Linux	free for download (PESCO_download/)	/	5	no	
Cognitron (Hampshire et al., 2021)	4	self-administered	web-based	multi-platform	attention, executive functions (reasoning, planning, working memory), processing speed	HTML5 with JavaScript	normative data (only within the tool), raw data generally available publicly or upon request	30-60 min	>100	no	
Cogniciti (Troyer et al., 2014)	1	self-administered	web-based	computer	divided attention, executive functions (spatial working memory, shifting), episodic memory	ASP.NET, JavaScript, and Adobe Flash	normative data, online testing (Cogniciti_free_testing)	20 min	4	no	
PEBL (Mueller & Piper, 2014)	2	self-administered	desktop software	computer	selective attention, executive functions (verbal and visuo-spatial short-term memory, inhibition, planning, problem-solving, and cognitive flexibility)	C++, Simple DirectMedia Layer	source code, free for download (PEBL_download)	/	70	yes	
THINC-it® (McIntyre et al., 2017)	1	in person	desktop software, mobile app	multi-platform	executive functions (working memory, set shifting), visuospatial coordination, and psychomotor speed	/	normative data (within the tool), free for download (THINC-it_download)	10-20 min	5	yes	user guide is available (https://progress.im/sites/default/files/attachments/thinc-it_v0.95_guide_0.pdf)
SLB (Gamito et al., 2016)	1	in person	wearable	computer	attention, executive functions (working memory), short term memory	Unity 2.5	normative data, free for download (SLB_download)	35 to 60 minutes	3	no	Virtual reality system
Box task (Kessels & Postma, 2018)	1	in person	desktop	multi-platform (computer, compatible with tablet)	executive functions (visuospatial working memory)	Microsoft Visual Basic	normative data, free for download (box_task_download)	/	1	no	

Table 2. *Summary table presenting the most salient features of the most accessible digital tools for the neuropsychological assessment of attentive and executive functions*

4. Discussion

4.1. AVAILABILITY AND ACCESSIBILITY OF DIGITAL TOOLS: WHERE ARE WE NOW?

Available norms, high validity, reliability and usability of digital tools are crucial components for a scientifically safe and sound adoption of these neuropsychological assessment tools in clinical practice and in research (Brinkman et al., 2014). One of the major advantages of digital tests over their paper-and-pencil ancestors consists precisely in the differential opportunity to automatize the collection and analysis of data and to share it quickly and easily, fostering cross-validation, the establishment of norms, the improvement and readaptation of the tools themselves thanks to accessible scripts and source code, and the generalizability of results by means of sharing the tools themselves. Additionally, sharing the raw data helps other researchers replicate the studies, thus potentially corroborating the original findings. It can be argued that sharing data is not always desirable, as clinical measures, be them behavioural or biomedical, provide sensitive information which may pose a threat to the privacy of patients or participants. While this is a legitimate concern, there are several safe ways to bypass the problem, starting from the anonymisation of data.

In contrast with these considerations, it emerged from the results of our search that only 5,16% of the selected studies employed free and open-source digital tools for the assessment of attentive and executive functions. When it comes to sharing data collected in the studies, in the form of raw or standardised data, only 4,36% of publications do share their data, and only 17,06% mention the availability of data upon reasonable request to the corresponding author. The availability of scripts and source code is even more limited, with a disappointing 3,57% of studies providing source code and only 1,19% providing them upon request. On a slightly more positive note, 47,62% of studies presented digital tools with publicly available normative data, while in 21,86% of publications normative data exist but are embedded within a tool with restricted access.

Critically, it also resulted from our search that there is an evident dissociation between the most employed digital tools and the most accessible ones. Indeed, the most employed digital tools for the assessment of attentive and executive functions are well-established, validated, reliable cognitive batteries such as the NeuroTrax and the CANTAB, whose reliability is supported by several studies exploring their psychometric properties and validity across different clinical populations and contexts. However, these tools are *de facto* commercial products and generally expensive, which severely limits their widespread adoption. On the other hand, the most accessible tools need further validation and, in most cases, the establishment of large norms. A few virtuous exceptions to the highlighted double dissociation between availability and accessibility is represented by the Cognitron battery (Bălăeţ et al., 2024; Giovane et al., 2023; Hampshire et al., 2022; Shibata et al., 2024) and a specific computerised version of the WCST (Steinke et al., 2021), two free and open-source digital tools. The former legitimately belongs to the most available digital tools and provides flexible assessment thanks to its self-administered, multi-platform nature and the availability of normative data (despite only accessible within the tool). On the other hand, different but similar computerised versions of the WCST (Leitner et al., 2023; Miles et al., 2022; Steinke et al., 2021; Xu & Xian, 2023) have been developed, making it a relatively common digital tool for the assessment of set-shifting and cognitive flexibility. Notably, the version developed by Steinke et al. (2021) resulted as the most accessible digital tool among the studies selected in our systematic review. While the validation status of the WCST in its electronic version is partial, the original version constitutes a well-known, established paradigm to assess cognitive flexibility, representing a gold standard in the assessment of executive functions. However, a caveat is necessary; the equivalence, in terms of reliability, validity and psychometric properties, between paper-and-pencil and digital versions, although similar, should not be assumed, as admitted by the authors themselves (Steinke et al., 2021). Additionally, as found by a study (Weber et al., 2002) comparing the performance between conventional and computerised attentive tasks in a psychiatric cohort, a negative computer attitude can lead to a statistically significant decrease in performance, thus limiting the reliability of digital assessment tools.

4.2. AVAILABILITY AND ACCESSIBILITY OF DIGITAL TOOLS: OPEN ISSUES

As it follows from the considerations above, while the implementation of digital tools is highly desirable for the advancement and improvement of neuropsychological assessment, both in clinical and academic settings, the snapshot of the current landscape provided by our work exposes several problematic aspects dampening the opportunity to capitalise on the advantages offered by this new generation of tools.

As sharply pointed out by Brinkman and colleagues (2014), most computerised assessments lack a strong empirical foundation or increased feasibility over traditional assessment methods. Indeed, the number of digital tools without established or accessible normative data is still high, and their psychometric properties are often yet to be thoroughly assessed. Secondly, the majority of our selected studies entailed the presence of a clinician or trained personnel for the administration of the tasks. One of the major differential advantages offered by the implementation of digital tools is the reduction of administration times and the possibility of tele- and self-administration. However, this opportunity is still not fully exploited, as the results indicate. Even more problematically, those digital tools which show higher degrees of validation, reliability, feasibility and whose psychometric properties have been explored more vastly, are generally distributed under expensive commercial licenses which heavily limit the testing and adoption of the tools themselves, thus leading to inequalities in the access to high-quality assessment and restricted generalization of the results.

4.3. Limitations of the present review

While the present work improves our understanding of the current scenario concerning the adoption of digital technologies for the neuropsychological assessment of attentive and executive functions, filling a gap in the literature and possibly constituting an orienting guide for policy makers and neuropsychologists, it is not exempted from different limitations.

First, we considered digital tools as a broad category, excluding only telephone-based assessments but considering altogether very different digital systems spanning from tele-administration of paper-and-pencil tests to virtual reality-based tasks encompassing computerised batteries and tests. Secondly, the methodological robustness of the studies was not systematically addressed, nor stringent evaluation criteria were adopted, as our intention was to include in the global descriptive analyses a wide range of studies so to gain insight into the availability and accessibility of digital tools.

Given the weaknesses of the present work, we recommend the reader to intend it as a serious, systematic and comprehensive guide to the landscape of digital tools for the neuropsychological assessment of executive functions, keeping in mind that more research is needed to expose more fine-grained characteristics of the object of the study.

4.4. FUTURE PERSPECTIVES

Drawing from our limitations, we encourage future studies to address these unresolved questions, considering other cognitive domains, the availability of applications for the assessment of children and adolescents, perhaps focusing on a subcategory of digital tools and with a more detailed description of the available studies.

For what concerns the adoption of free and open-source digital tools, we encourage researchers, healthcare professionals and policymakers to promote a collaborative culture of data, scripts and procedures sharing, so that other people can benefit from their work, replicate and validate it, possibly improve it or design useful variants of cognitive tasks. Publications characterised by a high degree of accessibility should be valued, so that free and newly developed digital tools can benefit from further validation and the establishment of reliable norms.

Finally, on a positive note, we want to illustrate a virtuous example from outside our main search. The development of the self-administered cognitive screening battery Auto-GEMS by researchers at the University of Padua (Contemori et al., 2024; Mondini et al., 2022; Montemurro et al., 2023) stands out as an impressive example of accessible innovation in cognitive screening tools. As a self-administered, computer-based tool, Auto-GEMS facilitates the rapid and comprehensive assessment of an individual’s cognitive state using a set of eleven items, capturing various cognitive abilities. This innovative tool aligns with modern trends of remote healthcare delivery, representing an evolution of its previous remote (Tele-GEMS) (Montemurro et al., 2023) and paper-and-pencil (GEMS) (Mondini et al., 2022) versions. By offering these flexible modes of administration, it accommodates different clinical needs and settings.

What makes Auto-GEMS particularly noteworthy is its psychometric rigor, having been tested on a large sample of 1308 healthy Italian participants, aged 18-93 years. This broad age range ensures the utility of the tool across various age groups, enhancing its clinical relevance.

In alignment with Open Science principles, Auto-GEMS is freely accessible under a Creative Commons license, making it a valuable resource for clinicians and researchers alike. A notable feature is the 'ready-to-use' version, which stores data locally on the user’s device in .csv format, ensuring data privacy and eliminating the need for external servers to retain sensitive information. Additionally, for remote administration, clinicians can request patients or caregivers to email the .csv files, facilitating efficient, secure data transfer. The Shiny app also allows users to compare individual scores with normative data, adding an extra layer of functionality for those seeking real-time analysis. The entire system is designed with privacy in mind: though the client's web browser connects to a server to download the necessary materials, no personal data is retained once the test is completed. The Auto-GEMS initiative demonstrates a commitment to user privacy and data security while advancing cognitive assessment practices in the direction of Open Science.

5. Conclusions

Our analysis of the current state of the availability of digital tools for the neuropsychological assessment of attentive and executive functions returned a neat scenario characterised by an evident double dissociation between availability and accessibility: a wide variety of such tools exist, and many have shown a good level of validation and reliability, with available normative data and thoroughly explored psychometric properties. However, the vast majority of these technologies are not accessible, thus undermining their widespread use and further validation. On the opposite side of the spectrum, promising studies introduce free, open-source and accessible in terms of collected data, scripts, procedures and norms, digital tools. Unfortunately, this category is under-represented, and few studies corroborate the validity, reliability, feasibility, sensitivity and specificity of such tools, thus undermining their safe and sound adoption.

To fill this gap, Open Science practices must be encouraged in order to capitalize on the intrinsic differential advantages of digital tools over their paper-and-pencil predecessors. While the development and validation of reliable assessment technologies undoubtedly comes with costs, thus partially justifying their distribution under commercial licenses, free, open-source and methodologically robust alternatives exist and should not be overlooked. By encouraging Open Science practices, fostering collaboration between independent teams and facilities and promoting a culture of transparency and accountability, these positive exceptions (Bălăeţ et al., 2024; Contemori et al., 2024; Giovane et al., 2023; Hampshire et al., 2022; Shibata et al., 2024; Steinke et al., 2021) can gain more visibility for the benefit of the scientific community, healthcare professionals and patients/clients themselves.

On a side note, a broader consideration about the significance of the growing adoption of digital tools with respect to the evolution of the role of the neuropsychologist is necessary. While the automatization of data collection, correction and the implementation of technology in clinical settings may pose a threat to the patient-psychologist relationship (Vitacca et al., 2022), it introduces enormous benefits in terms of administration times, efficiency, precision and costs, enabling professionals, including neuropsychologists, to focus on more abstract and important aspects of their clinical practice. By ensuring high quality measurements and analyses in a shorter time, the systematic yet conscientious adoption of digital tools for neuropsychological assessment can revitalize clinical practices, giving the opportunity to professionals to invest their intellectual energies into the interpretation of the results, the selection of the most appropriate assessment tools, the designing of useful variants of cognitive tasks, the investigation of meaningful patterns and correlations between measures, and the development of effective rehabilitation and intervention programs.

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