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Applications of Technology in Neuropsychological Assessment

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Abstract

Most neuropsychological assessments include at least one measure that is administered, scored, or interpreted by computers or other technologies. Despite supportive findings for these technology-based assessments, there is resistance in the field of neuropsychology to adopt additional measures that incorporate technology components. This literature review addresses the research findings of technology-based neuropsychological assessments, including computer-, and virtual reality-based measures of cognitive and functional abilities. We evaluate the strengths and limitations of each approach, and examine the utility of technology-based assessments to obtain supplemental cognitive and behavioral information that may be otherwise undetected by traditional paper and pencil measures. We argue that the potential of technology use in neuropsychological assessment has not yet been realized, and continued adoption of new technologies could result in more comprehensive assessment of cognitive dysfunction and in turn, better informed diagnosis and treatments. Recommendations for future research are also provided.

Keywords

Neuropsychological assessment; Technology; Computerized Testing; Virtual Reality

Historically, neuropsychological assessment has relied on paper and pencil based tests to assess cognitive abilities, and studies conducted with these tests have generated thousands of scholarly articles promoting their strengths and debating their weaknesses. However, in recent years, increasing numbers of researchers and clinicians have started to use various technologies to improve the efficiency, reliability, and cost-effectiveness of neuropsychological assessment. Rapid advances in technology, including improved computer programming, have allowed many assessment measures to be administered, scored, or interpreted without the direct interaction of a clinician.

The recent surge in technological developments has also affected the way that individuals carry out their everyday activities. In contrast to current older adult cohorts, children and teenagers born in the new millennium have never known a day without technology, such as the internet, cellular phones, and laptop computers. This increase in technology use in recent generations has produced an apparent cohort effect in the comfort and ease in which individuals use electronics. In fact, recent studies have found that cohorts with greater exposure to computers perform better on computer-based assessments than those with less computer experience (Tun & Lachman, 2010), suggesting positive effects of familiarity with technology on computer-based testing. In addition, major college and graduate school entrance exams (e.g., SAT or GRE) are computer-administered, and neuropsychologists are occasionally asked to recommend academic accommodations for these students. Thus, having neuropsychological examinations that are computer-based would provide the

clinician with added information about computerized testing abilities. Given that this pattern of technology use is likely to continue increasing in coming decades (Riva, 2003), it is important to consider whether neuropsychological assessment should adapt to technological developments so as to maintain status with the experiences of clients (e.g., exposure and comfort with computers).

Questions and Aims of this Review

While other reviews have assessed the psychometric properties of computer-based assessments (e.g., Wild, Howieson, Webbe, Seelye, & Kaye, 2008), this paper focuses on the utility of technology use in the field of neuropsychology and future directions for research. The following questions are addressed:

1. What are the strengths and weaknesses of computer- and virtual reality-based neuropsychological assessment of cognition and everyday functioning?
2. How can technology-based measures add value to neuropsychological assessment data?
3. What are the major factors to be considered when developing or implementing technology-based assessments?
4. What are future clinical and research directions within the field of neuropsychological assessment related to technology use?

Literature Search Procedure

PsycINFO, PubMed, and IEEE Xplore databases were searched between July 1, 2012 and October 10, 2012 for this literature review. Searches included terms for cognition and/or a specific neurological disorder with the modality for assessment (i.e., computer-based, virtual reality); however, these terms varied by the modality for assessment. Search terms for each modality are provided in Table 1.

Inclusion Criteria

Studies were included based on the following criteria: participants of all ages with or without cognitive impairment or neurological disease (e.g., dementia, Parkinson's disease, brain injury). Studies were compared based on sample demographics. For example, studies with adult participants were only compared to other studies using adults (not children). Studies were excluded if normative participants demonstrated severe psychopathology (e.g., schizophrenia, bipolar disorder) and/or severe intellectual, physical, or neurodevelopmental disability (e.g., mental retardation, cerebral palsy). Studies that used interventions, such as cognitive rehabilitation or pharmacological regimens, were included only when baseline measures were provided. Technologies such as robots/androids or other physical assistive devices (e.g., intelligent wheelchairs or robotic prostheses) were excluded. Book chapters and dissertations were included when appropriate, such as states of the field or reviews of current research. Publication date was not a consideration for exclusion. Industry-sponsored studies of technology were excluded due to the potential conflict of interest. Of the 167 articles initially found in the literature search, 108 were included for this review, including 11 studies of individual computer-based neuropsychological tests (see Table 2), 80 studies using 6 different computerized neuropsychological test batteries (see Table 3), and 17 studies evaluating 8 different virtual reality-based assessments (see Table 4).

Cognitive Assessment using Computers

Computer-based assessment consists of a wide range of approaches that use a computer interface to administer, score, or interpret cognitive tests. Bauer, Iverson, Cernich, Binder,

Ruff, and Naugle (2012) define computer-based assessments as “any instrument that utilizes a computer, digital tablet, handheld device, or other digital interface instead of a human examiner to administer, score, or interpret tests of brain function and related factors relevant to questions of neurologic health and illness”, (p. 2). This section summarizes briefly the development of computerized assessment and the adaptation of paper and pencil measures into computer-administered tests (see Noyes & Garland, 2008 for a full review of such comparisons). We also discuss the development of neuropsychological test batteries that were specifically designed for computer administration, highlighting the use of these tests with clinical populations (e.g., dementia, Parkinson’s disease, TBI).

Computer-Based Assessment

Although computer-based assessment is discussed as a newer approach to cognitive testing, military and sport psychology fields have used computerized assessments since the 1980s to quickly and efficiently evaluate cognitive functioning. Within the United States military, computerized batteries such as the Automated Neuropsychological Assessment Metrics (ANAM) have been used for both pre- and post-deployment assessment. This data collection has led to an excellent database for development of specialized measures, such as the ANAM TBI battery (Vincent, Roebuck-Spencer, Gilliland, & Schlegel, 2012). Reliance on computer-based assessment has permitted ease in administration and data collection with thousands of military personnel within clinics and abroad (for a comprehensive review of the ANAM development see Reeves, Winter, Bleiburg, & Kane, 2007). Similarly, clinical sports psychologists have used computerized batteries, such as ImPact or CogSport (e.g., Allen & Gfeller, 2011; Broglio, Ferrara, Macciocchi, Baumgartner, & Elliott, 2007; Maerlander et al., 2010) to assess for mild traumatic brain injury (e.g., Lovell et al., 2003; Macciocchi, Barth, Alves, Rimel, & Jane, 1996) and to inform return-to-play decisions (e.g., Lovell, 2002; Lovell, Collins, & Bradley, 2004; Schatz, Pardini, Lovell, Collins, & Podell, 2006). Within the fields of military and sport psychology assessment, there is general acceptance of technology-driven assessment as an efficient, well-standardized and readily accessible approach to testing (Lovell, 2002), and such assessments have become the rule, rather than the exception.

Computer-based assessment has also infiltrated the field of neuropsychology beyond the military and determining the effects of concussions in sports medicine. Neuropsychologists who work with cognitively impaired populations likely use at least one assessment measure that relies on a computer for administration, scoring and/or interpretation. As seen in Table 2, several studies have investigated the psychometric properties of computerized versions of paper and pencil neuropsychological tasks. These studies have concentrated on measures of executive skills and higher order functioning, including the Tower of Hanoi (5 studies), WCST (4 studies) and Stroop (2 studies). In general, these studies found similar, if not improved, reliability (e.g., fewer scoring errors) for the computer-based administration compared to the original tests (e.g., Mataix-Cols & Barts-Faz, 2002). The studies also showed that normative data that exists for traditional versions of tests cannot simply be applied to computerized versions as performances on traditional and computer-based administrations are not directly comparable (Steinmetz, Brunner, Loarer, & Houssemand, 2010). For example, computerized versions of the Tower of Hanoi test were found to increase trial-and-error approaches (Noyes & Garland, 2003) and reduce load on working memory (Williams & Noyes, 2007). Embedded measures of response time have also been used to assess constructs of processing speed (e.g., Edwards et al., 1996). However, aside from more micro-level measures of processing speed and/or response latency (e.g., time-stamped latencies for moves on the Tower of Hanoi; Guevara et al., 2009), the computer-based administrations of paper and pencil neuropsychological tests did not capitalize on the opportunity to obtain additional diagnostically useful cognitive and behavioral information.

The above findings represent a significant gap in the application of technology to improve neuropsychological assessment.

Attempts to address this gap have led researchers to design computer-administered tests to improve measurement constructs. This process often requires internal measures designed to capture underlying cognitive performances. For example, time sensitive parameters, such as reaction time (e.g., Robbins et al., 1994) or inspection time (e.g., Kush, Spring, & Barkand, 2012), can be measured more accurately using computers. In addition, many computerized tests use algorithms for administration purposes. For instance, “adaptive” testing approaches consist of algorithms that select future test items based on prior performance. This approach allows for more precise assessment of cognitive limits (e.g., floor or ceiling) while also reducing test administration time by discontinuing the test after the minimum criteria have been reached. Further, these algorithms can be used to improve sensitivity to a particular disorder by targeting hallmark symptoms (e.g., executive functioning deficits in Parkinson’s disease; Hanna-Pladdy et al., 2010), which may assist neuropsychologists in differential diagnoses.

To target specific disorders, and thus improve sensitivity to detect characteristic deficits, batteries of computerized tests have also been developed for both clinical and research purposes. Table 3 shows data from studies that examined the sensitivity and specificity of computer-administered test batteries for the detection of cognitive disorders, including mild cognitive impairment, dementia, Parkinson’s disease and traumatic brain injury (TBI). For example, the CogState and CNS Vital Signs have differentiated healthy controls from individuals with TBI (e.g., Gualtieri & Johnson, 2008) and dementia (e.g., Darby et al., 2011; Gualtieri & Johnson, 2005; Levinson, Reeves, Watson, & Harrison, 2005; Lim et al., 2012). In addition, the CAMCOG and CANTAB batteries have successfully distinguished controls from clinical populations, including MCI (Junkkila, Oja, Laine, & Karrasch, 2012), Alzheimer’s disease (Egerhazi, Berecz, Bartok, & Degrell, 2007), and Parkinson’s disease (McKinlay et al., 2009). Fewer studies have attempted to differentiate between different neurological disorders (e.g., Alzheimer’s disease versus Huntington’s disease; Rosser & Hodges, 1994 or Parkinson’s disease; Burton, McKeith, Burn, Williams, & O’Brien, 2004).

Cognitive Assessment Using Virtual Reality

Virtual reality encompasses a wide variety of technologies and devices to assess manipulation of objects (including the self) in a virtual space and time. For applications in psychology, these environments are usually three-dimensional, allowing for a 360-degree view of the virtual landscape, and allow for interaction with objects in the environment (Kalawsky, 1996). Virtual environments can range from basic rooms for navigation tasks to detailed spaces (e.g., office, classroom) to assess more complex activities. Furthermore, virtual reality technologies differ in the type of immersion used, including (a) non-immersive three-dimensional computer-screens with a mouse, joystick, or sensor-based gloves, (b) semi-immersive large screen displays using shutter glasses, and (c) full immersive environments with a “green screen” and head-mounted display (Costello, 1997; Kalawsky, 1996). For the purpose of this review, we included all types of virtual reality technologies that have been used to assess cognitive and everyday performances. This section provides a discussion of the initial developments of virtual reality for cognitive assessment and the more recent applications of these technologies to assess everyday functioning (e.g., grocery shopping). We also examine the effects of environmental distractors on cognitive and IADL performance. In particular, we highlight the use of virtual reality as a tool to obtain behavioral and cognitive information beyond what is collected in traditional cognitive assessments.

Development of Virtual Reality Assessments

Similar to computer-based assessments, the beginning of virtual reality-based cognitive assessment involved integrating computerized versions of traditional paper and pencil based tests into a virtual environment. Theoretically, this integration allowed clinicians to observe the participant's approach to task completion in a simulated environment that may better represent everyday life. Table 4 contains findings from virtual reality-based neuropsychological assessments, including studies evaluating their sensitivity to various cognitive disorders (e.g., mild cognitive impairment, dementia, TBI), and comparisons with traditional paper and pencil based tasks. For example, one research group developed a three-dimensional test for a virtual reality platform that mimics the Wisconsin Card Sorting Test ("Look for a Match"; Elkind, Rubin, Rosenthal, Skoff, & Prather, 2001). When compared to the manual administration of the WCST, participants appeared to do more poorly on the virtual reality-based version; however, they reported enjoying the virtual reality test more than the traditional WCST (Elkind et al., 2001). The authors concluded that the distractions present during the virtual reality administration may have negatively affected performance; however, other explanations, such as task difficulty or novelty should be investigated. Thus, virtual reality allows for external stimuli to be part of the assessment battery while still measuring targeted cognitive abilities. Researchers have suggested that these distractions may improve the ecological validity of tasks because the test will better represent cognitive performance with real-world interruptions (Rizzo et al., 2006; Parsons et al., 2011). Consistent with computerized versions of cognitive assessments, virtual reality measures require demonstration of their validity and reliability as well as unique normative data specific to the individual test (Schatz & Browndyke, 2002).

As seen in Table 4, virtual reality tasks have been used to assess the cognitive variables of attention, memory, and executive functioning. However, because the virtual reality approach could change the fundamental nature of a task, one should not assume that the same cognitive constructs are being measured by similar traditional and virtual reality-based measures. Studies in Table 4 highlight the utility of virtual reality scenarios for expanding on traditional tests, including multi-tasking components and/or simulation of higher-order tasks that demand multiple cognitive domains (e.g., working memory, attention, and visual spatial skills while learning in a classroom; Rizzo et al., 2006). Table 4 also shows that virtual reality tests have been developed to assess multi-tasking in a simulated virtual environment, including running errands and completing kitchen tasks. These studies have targeted clinical populations for stroke (Rand, Basha-Abu, Weiss, & Katz, 2009), Parkinson's disease (Albani et al., 2010), and TBI (Zhang et al., 2003) to identify cognitive deficits associated with completing everyday tasks, such as purchasing groceries or making meals.

Manipulation of External Stimuli in Virtual Reality Assessments

One of the important questions that is often asked in neuropsychology is whether cognitive performances are affected by external stimuli (e.g., everyday stressors or distractions; Pugnetti et al., 1995; Rizzo & Buckwalter, 1997). More specifically, this question considers whether neuropsychological testing conducted in a plain room with limited distractions is an accurate portrayal of "real world" abilities. Adding controlled distractions to testing could improve ecological validity. Emulating real-world combat scenarios, Parsons and colleagues (2011) recently developed a virtual-reality Stroop task (VRST) for assessment of TBIs without external symptomatology. The VRST consists of a three-dimensional administration of the Stroop task while "immersed" in a virtual Humvee in either low-threat or high-threat scenarios (defined by intensity of environmental threat). The initial study revealed that when individuals with TBIs completed the VRST in a military simulation, significant differences were present for the Interference condition in both the high and low threat conditions; these

differences did not achieve significance for the paper and pencil or ANAM versions of the Stroop task.

More recently, Parsons and colleagues (2012) conducted a similar study using a virtual reality version of the Paced Auditory/Visual Serial Addition Tests (VR PA/VSAT; staged in a virtual military environment), comparing paper and pencil tests with virtual reality version of the PASAT over four sessions. In a military cohort, they found that the VRPASAT and VRPVSAT did not correlate with the paper-based PASAT, and, relative to the paper version, revealed slower mathematical processing and reaction times for the first two sessions, but not sessions 3 and 4, which are considered more cognitively challenging (Parsons et al., 2012). Taken together, these findings using virtual-reality based cognitive assessments suggest that including simulated distractions within the testing environment may lead to a better understanding of the influence of external stimuli on cognition in a real-world scenario.

Additional virtual reality assessments have been developed that are not based on traditional paper and pencil tests. Parsons and colleagues (2008a) developed the Virtual Reality Cognitive Performance Assessment Test (VRCPAT) as an alternative approach to a traditional cognitive screening. In a 15-minute battery of virtual reality-based tests (e.g., navigation of a virtual environment and delayed recall for items viewed in the scenario), the VRCPAT yields two total scores – one for learning and one for memory, which have been found to correlate significantly with traditional assessments of memory, attention, processing speed, and executive functioning (Parsons, Silva, Pair, & Rizzo, 2008a). However, poorer performances are evident when external distractions are present in the virtual environment, relative to assessments without any additional distracting stimuli (Parsons et al., 2008a; Parsons et al., 2011). Here we see that measures of learning and memory, which generally rely on components of attention, are affected by environmental distractions. This finding suggests that external stimuli in a virtual environment could be used to gather behavioral data of distractibility and attentional lapses that may otherwise go unmeasured in a traditional neuropsychological evaluation.

Attention deficit research has also explored the utility of controlled distractions in virtual reality-based assessments. Rizzo and colleagues (2006) developed the Virtual Classroom in which standardized neuropsychological tests are converted into computer-administered versions, and then embedded into an interactive, three-dimensional classroom. An assessment in the Virtual Classroom not only provides the total score for the embedded test (e.g., Boston Naming Test, Stroop Color-Word Test), but also gathers information about distractibility in real-time (obtained through an algorithmically-defined count of head movement away from stimuli). The administrator can control the amount and types of distractors that are present in the classroom (e.g., other students talking or moving in their seats, activity out a classroom window). Preliminary comparisons of the Virtual Classroom with continuous performance tests for ADHD have revealed that the Virtual Classroom better classified children with ADHD (Adams, Finn, Moes, Flannery, & Rizzo, 2009). Additional measures of distractibility from the Virtual Classroom (e.g., head movement tracking) also revealed greater inattentive symptoms in children with ADHD relative to controls (Parsons, Bowerly, Buckwalter & Rizzo, 2007). These data of real-time distractibility during testing may provide a more thorough and/or more ecologically valid assessment of cognitive performance for children with ADHD (Parsons et al., 2007). Furthermore, such additional measures could better inform diagnoses as well as treatments for behaviorally-focused disorders, such as ADHD or Conduct Disorder. While supplemental measures of distractibility and inattention are a highlight of virtual-reality technology, simulated environments have also assessed the relationship between cognitive domains and everyday functioning.

Assessment of Everyday Functioning Using Virtual Reality

The ability to incorporate complex environments into testing scenarios has allowed for measurement of real-world cognitive abilities that are otherwise constrained to abstract tasks in the laboratory. Virtual reality assessments provide a variety of environments, including driving simulations and grocery stores, for assessing cognitive and functional status. Virtual simulations of everyday tasks, such as driving (e.g., Legenfelder, Schultheis, Al-Shihabi, Mourant, & DeLuca, 2002; Schultheis, Rebimbas, Mourant, & Millis, 2007), shopping (e.g., Kang et al., 2008), and meal preparation (e.g., Zhang et al., 2001; Zhang et al., 2003), provide a safe and controlled environment for assessing functional capacities of clinical populations. Furthermore, because these environments are controlled by the experimenter, distractions or interruptions can be implemented to assess higher functions (e.g., multi-tasking and executive functioning) and target cognitive deficits that characterize specific disorders. Here we discuss the applications of virtual reality to assessing instrumental activities of daily living (IADL), including driving simulation and functional assessment of everyday tasks.

Driving simulation—Numerous studies have used driving simulation to determine specific cognitive demands needed during driving navigation. Although this large body of research is beyond the scope of this review, the efforts of researchers in this area bear mention. Virtual reality driving simulators have been used to assess various aspects of driving (e.g., distractibility, reaction time) in many clinical populations, including dementia (e.g., Rizzo, McGehee, Dawson, & Anderson, 2001), multiple sclerosis (e.g., Schultheis, Weisser, Manning, Blasco, & Ang, 2009), brain injury (e.g., Cox et al., 2010; Schultheis et al., 2006; Wald, Liu, Hirsekorn, & Taylor, 2000), and spinal cord injury (Carlozzi, Gade, Rizzo, & Tulskey, 2012). Driving simulators are becoming increasingly more realistic, including use of full-immersion screens and multi-sensory feedback, which has further improved their similarity to a real-world driving experience (e.g., Mayhew et al., 2011; Wang et al., 2010). Although some research has provided support for virtual reality simulation testing in place of self-report data and testing for underlying cognitive domains that are necessary for driving, such as sustained attention, problem-solving, and multi-tasking (e.g., Gaspar, Neider, & Kramer, 2013), other findings suggest that driving simulators may not be adequate for determining driving abilities and risk without supplemental information (e.g., Asimakopulos et al., 2012; Lundqvist, Gerdle, & Ronnberg, 2000). Thus, driving simulators provide an opportunity for obtaining basic information about driving abilities in a safe environment; however, driving simulators may be better used in combination with other assessments of cognitive and physical functioning for a more comprehensive assessment of skills needed for driving (Lew et al., 2005; Patomella, Tham, & Kottorp, 2006). For additional articles about driving simulation see Calhoun and Pearson (2012) or Schultheis et al. (2007).

Everyday functioning—In addition to general driving abilities, virtual reality has been used increasingly in the assessment of everyday tasks. For example, the Multiple Errands Test (MET; Alderman, Burgess, Knight, Henman, 2003; Shallice & Burgess, 1991), a complex test of executive abilities that was developed for assessment of frontal lobe lesions and carried out in a shopping mall, has been adapted for administration in virtual environments. These adaptations include the Virtual Errands Test (VET; McGeorge et al., 2001), which assesses planning abilities associated with multi-tasking, and the Virtual Multiple Errands Tests (VMET; Rand et al., 2009), which measures strategy and interweaving of task information in addition to general memory and executive skills. In the VMET, participants navigate a virtual supermarket to obtain items from a predetermined shopping list. In addition, they must obtain information (e.g., time the store closes) and obey rules to promote planning and efficiency (e.g., cannot go to the same aisle twice). Studies

have found that the VMET correlates strongly with other measures of executive function and attention (e.g., Dysexecutive Questionnaire, Test of Everyday Attention). The VMET has also distinguished among different age groups of cognitively healthy adults, as well as participants who have experienced stroke (Rand et al., 2009; Raspelli et al., 2010) or Parkinson's disease (Albani et al., 2010) from healthy controls. These findings suggest the utility of evaluating performance of a complex task like shopping in a virtual environment, which is both safe and controlled.

Research has also evaluated the utility of a virtual kitchen to assess meal preparation skills (e.g., preparing soup and a sandwich). For example, Zhang and colleagues (2001) developed a computer-simulated kitchen to measure deficits in problem solving, sequencing, and speeded processing. Their virtual reality meal preparation task has distinguished between TBI and healthy controls (Zhang et al., 2001) with satisfactory construct validity and test-retest reliability (Zhang et al., 2003). They also found that performance on their virtual reality meal preparation task correlated strongly with independent evaluation of IADLs by occupational therapists (Zhang et al., 2003). These findings demonstrate some of the possibilities for virtual reality technology in clinical settings, and the utility of virtual reality to gather information that would otherwise go unnoticed in a traditional neuropsychological assessment. Although the previous studies indicate significant progress, challenges remain.

Computer-Based and Virtual Reality Assessments: Conclusions and Future Directions

The use of technology in neuropsychological assessment is continuing to expand and improve upon traditional approaches of the past. However, along with advantages of using technology-based assessment come challenges. Although some challenges are common across all types of neuropsychological assessment (e.g., establishing psychometric properties and adequate normative data), other limitations are unique to assessments driven by technology. Below we highlight strengths and weaknesses of technology in neuropsychological assessment and consider directions for future research.

What are the strengths and weaknesses of computer- and virtual reality-based neuropsychological assessment of cognition and everyday functioning?

Strengths

Research suggests that current computerized assessments are comparably reliable and valid to other neuropsychological testing measures when used with appropriate normative data (e.g., Mataix-Cols & Bartes-Faz, 2002; Schatz & Browndyke, 2002). Computerized tests have the advantage of algorithmic design, which can be used to tailor testing for specific populations (e.g., Hanna-Pladdy et al., 2010; Wouters et al., 2011). Computerized tests have also been shown to provide increased ease and standardization of administration (Fillit, Simon, Doniger, & Cummings, 2008), reduction in errors during scoring and interpretation (Koski et al., 2011), and readily accessible assessment without significant time devoted to preparation of materials (Koski et al., 2011). Notably, there are several computerized batteries that are more comprehensive and sensitive to mild cognitive deficits (e.g., CANTAB, Mindstreams), whereas other batteries appear to be better suited for brief cognitive screenings to determine whether full evaluation is necessary (e.g., ANAM, CogState, CNS Vital Signs). Findings regarding test-retest reliability, sensitivity, and specificity vary widely among the batteries, suggesting that standardization of approaches and improvements should be considered for future versions (see Wild et al., 2008).

Clinical application of virtual reality has provided new opportunities for assessment, including customization for target populations, specific cognitive domains, and unique settings. Virtual reality scenarios allow for measurement of simulated everyday tasks in a safe and controlled environment (Rizzo et al., 2006). Furthermore, the opportunity for researchers and clinicians to assess the influence of environmental stimuli (e.g., distractions, interruptions) on cognitive performance may provide a more ecologically valid assessment of everyday skills (Parsons et al., 2007). Thus, virtual reality platforms have promoted the collection of additional cognitive and behavioral information about neuropsychological testing performance beyond the traditional data obtained through paper and pencil assessments.

Weaknesses and Limitations

Disadvantages to technology-based testing are not to be dismissed. These include general technological issues, such as variations in computer hardware, and the currently limited information on psychometric and normative properties for different clinical populations (Bauer et al., 2012). Addressing these issues will require full psychometric evaluations and adjustments to future versions of virtual-reality assessments in order to improve internal and ecological validity, test-retest reliability, and utility for various populations (Bauer et al., 2012; Retzlaff & Gibertini, 2000). These limitations are consistent with many of the initial challenges posed when developing any new assessment, and thus are not beyond the capacity of researchers to overcome. In addition, performance on technology-based assessments may be influenced by knowledge of computers or other technology (Fazeli, Ross, Vance, & Ball, 2012), suggesting that cohort effects based on comfort with using new technology may need to be investigated.

Limitations unique to virtual reality are dominated by physiological concerns (e.g., motion sickness). There is currently no research consensus on the influence of virtual motion sickness on cognitive performance in virtual environments. Evidence has suggested tolerance of motion sickness in older adults (Flynn et al., 2003; Mullen, Weaver, Reindeau, Morrison, & Bedard, 2010), and most studies with virtual reality technology incorporate measures for motion sickness after completing the assessment. However, studies have not investigated the impact of sub-threshold motion sickness on cognitive performance and this issue requires further investigation (e.g., Nichols & Patel, 2002).

The extent to which virtual reality simulations reflect the real experiences of individuals varies widely among users. For some individuals, the novelty of wearing a head-mounted viewer may be enough to alter their behaviors, whereas others are more motivated because they find the technology to be interesting or even enjoyable (Gaggioli, 2012). Evidence for ecological validity of virtual reality has generally been limited to comparisons between traditional and virtual reality assessments, which have demonstrated adequate construct validity (e.g., Matheis et al., 2007). Similarly, evidence for effects of computer experience has produced mixed results (e.g., Fazeli, et al., 2012) and requires further investigation. Consistent with the disadvantages of computer-based systems, virtual reality assessments are subject to greater individual variability, which has been associated with differences in computer experience, as well as learning and adaptation to the virtual environment (see Chen, 2000) for a thorough discussion of individual differences in virtual reality). In addition, virtual-reality assessments are relatively high-cost technologies that require regular maintenance. Cost-efficiency should be considered relative to costs of paper-and-pencil measures. As with any computer-based technology, data gathered from virtual reality tasks needs to be securely stored to preserve patient privacy. While the issue of privacy and data security is important, it is regularly encountered in clinical settings. And with proper security measures in place, this should not be considered a weakness of virtual-reality technology.

How can technology-based measures add value to neuropsychological assessment data?—Advances in technology offer the opportunity to gain valuable information from assessment that is not obtained through paper and pencil measures, such as algorithmically-defined approaches to a particular test (e.g., organization, planning), evaluation of pauses, perseverations, and domain-specific errors, and/or response times in very specific measurements (e.g., Sahakian & Owen, 1992). By embracing the utility of technology to provide additional measures, neuropsychological assessment could expand the ways in which cognitive deficits are evaluated and ultimately treated. In addition, using technology could improve the psychometric properties of neuropsychological assessments, including better inter-rater reliability in scoring procedures, more consistent administration procedures across clinics, and ultimately more confidence in final reporting of findings. Further, the infiltration of technology into everyday life has become so significant that differences in familiarity with computers can affect performance on standardized cognitive tasks (e.g., Tun & Lachman, 2010). If technology use continues to increase, it will be imperative that neuropsychological assessments incorporate more tasks that reflect this adaptation to technology in everyday life (Bauer et al., 2012).

Virtual reality technologies have provided opportunities for neuropsychologists to evaluate clients' cognitive and everyday abilities within simulated environments, which have supplied valuable information about the effect of environment on cognitive performance. For example, the assimilation of computer-based tests of memory and attention in a virtual classroom setting revealed that increased numbers of environmental distractors affected individuals with ADHD significantly more than controls (e.g., Adams et al., 2009). In addition, findings from virtual reality research have provided evidence for the ability of technology to acquire additional information about participant performance, such as head tracking as a measure of attention and distractibility (Parsons et al., 2007; Parsons et al., 2011). These added measures of attention complement the traditional neuropsychological tests of short-term and sustained attention, providing a more thorough evaluation of real-world indicators of attentional problems. Ideally, these supplementary measures will provide additional information to more accurately diagnose attentional disorders (e.g., ADHD), and in turn inform effective treatments for deficits on a spectrum.

In addition to cognitive processing domains, neuropsychologists have begun to seek ecologically valid assessments of everyday functioning. Assessment of IADLs has varied from virtual reality environments, such as shopping malls and grocery stores, to staged apartments and homes equipped with sensor technologies. Findings from virtual reality studies have suggested that individuals with cognitive impairments exhibit greater difficulties with driving and navigation than older adult controls (e.g., Hagler et al., 2010; Rizzo et al., 2001). Recent research movements in the fields of occupational therapy, physical therapy, nursing, as well as psychology have focused on everyday functioning and longitudinal monitoring of daily activity performance (Kaye, 2008; Marcotte, Scott, Kamat, & Heaton, 2010). This transition from general cognitive abilities to real-world assessment has sparked development of tests specific to everyday functional skills and improvements in ecological validity of cognitive testing. For example, sensor-based assessment of gait and physical strength have been associated with various cognitive disorders (e.g., Buchman, Boyle, Leurgans, Barnes, & Bennett., 2011; de Melo Coelho et al., 2012; Hagler et al., 2010; McGough et al., 2011), and assessment with non-invasive sensors in smart home testbeds or resident homes have revealed behavioral patterns of activities that relate to cognitive disorders (e.g., Dawadi et al., 2011; Hayes et al., 2008). The continuous measurement data afforded by these technologies are beyond the capabilities of traditional assessment procedures, including self-report (Stanley & Osgood, 2011), and can provide a more comprehensive assessment of patient functioning. Relative to traditional paper and pencil

tests of cognitive domains, these findings suggest that technology-based assessment could contribute additional valuable information to aid with diagnosis and treatment.

What are the major factors to be considered when developing or implementing technology-based assessments?—Future developments of technology-based assessments should consider several issues for new tests, including the influence of cohort effects (e.g., knowledge base of technology), cost-effectiveness, construct validity and standardization procedures. Research has suggested that individuals with greater computer experience perform better on computer-based assessments than those with less computer experience (Iverson et al., 2009; Tun & Lachman, 2010). Thus, user-friendly interfaces should be used to promote ease of use for individuals with less experience. In addition, the cost of equipment, such as replacing paper-and-pencil tests with computers or purchasing virtual reality systems, is a consideration for increased use in common assessment procedures. Currently these technologies may exceed the financial limits of a clinic. As with other technologies, as virtual reality becomes more commonplace, costs will likely decrease; however, cost-benefit analyses should be conducted to ensure accuracy of assessment while maintaining a reasonable cost (Crandall & Cook, 2012). Technology-based assessments may promote shorter evaluation times while gathering more cognitive and behavioral data than a traditional neuropsychological assessment. Research should also investigate the construct validity of new technology-based assessments to address whether the cognitive constructs tapped by traditional paper-and-pencil tests are comparable to those assessed by computerized or virtual-reality versions. As with any new measure, psychometric and normative properties of technology-based assessments should also be researched and provided to users for accurate evaluation and interpretation of clinical data.

Using technology for assessment also poses an added challenge in that equipment can vary by laboratory or user. For example, the speed of a computer processor can affect the accuracy with which reaction time speed is measured. Thus, equipment standardization may be necessary in developing technology-based assessments with consistent results across administration sites. In addition, research has suggested that computer-based assessments, as well as virtual-reality tasks, are subject to individual variability. Studies have found that familiarity with computers (Tun & Lachman, 2010), motivation and interest in the technology (Gaggioli, 2012), and ease of learning and adaptation to virtual environments (Chen, 2000) can influence performance on computerized assessments. Therefore normative bases should include base rate influences of individual variability when developing new assessments.

What are directions for future clinical and research within the field of neuropsychological assessment related to technology use?

Computerized and Virtual Reality Assessments

Future research of technology-based assessment should focus on improving normative properties and standardization of current measures (e.g., sensitivity to target populations), as well as developing assessments that are sensitive to processes that cannot be assessed easily using paper and pencil measures (e.g., reaction time). Also, studies should assess how technology knowledge (e.g., being “tech-savvy” versus a first-time computer user) affect performance on assessments administered via technological modalities (e.g., computer, virtual reality). In addition, functional brain imaging to evaluate whether neuroanatomical correlates are similar between virtual reality and traditional tests of everyday functioning may also be useful to guide development of new assessments. Lastly, comparisons should be

made between real-world performances of activities of daily living and virtual reality assessment designed to resemble everyday tasks.

Smart Environments

Recent strides in computer science have led to activity recognition in passive monitoring of IADLs (e.g., Dawadi et al., 2011; Rashidi et al., 2011; Singla et al., 2010). Smart environment studies have revealed relationships between direct observations of real-world tasks, such as cooking and cleaning, and sensor-based data (e.g., motion sensor activity) from a smart environment (Dawadi, Cook, & Schmitter-Edgecombe, in press). Collaborative work with computer scientists has revealed that smart environment data, such as activity patterns derived from motion sensors, can differentiate normal older adults from individuals with cognitive impairment (Dawadi et al., 2011). Additional efforts are concentrating on identifying behavioral changes associated with normal aging and cognitive decline (e.g., Hayes et al., 2008; Kaye et al., 2011), as well as communicative systems (e.g., intercoms) and prompting technologies to promote independent living and delay the need for long-term assistive care (Schmitter-Edgecombe et al., 2013; Seelye et al., 2012). Longitudinal monitoring of IADLs in real-world settings (e.g., patients living in smart homes) is ongoing, and finding correlations between cognitive and everyday functioning over time could better inform preventative and diagnostic efforts, as well as treatments in cognitive decline (Schmitter-Edgecombe et al., 2013). Data obtained through passive sensor monitoring could provide supplemental information about everyday functioning that is not subject to self-report bias and subtle, yet informative changes that may otherwise go unnoticed (Stanley & Osgood, 2011). Given that the response to smart home technology is generally positive (e.g., Courtney, 2008; Demiris, Hansel, Skubic, & Rantz, 2008; Wild et al., 2012), research to improve clinical utility of smart homes is necessary if wide-spread use of sensor systems is desired; however continued caution in privacy matters should be taken into account in future research.

Real-Time Data Collection

Another area of interest for neuropsychologists may be patient data collection in real-time outside of the clinic. Ecological momentary assessment (EMA) is a data collection approach using telephone-, PDA-, or tablet-administered self-report questionnaires. EMA is used to obtain subjective measures multiple times per day (Smyth & Stone, 2003; Stone & Shiffman, 1994). Because traditional neuropsychological assessments occur, most often, during a single appointment, the data may not reflect daily changes or fluctuations in cognition over the day or the week. One of the greatest advantages of EMA is that researchers can gather data in 'real time', which may result in less bias than in-clinic data resulting from recollective self-report (Jones & Johnston, 2011; Shiffman, Stone, & Hufford, 2008). Greater accuracy in EMA approaches could be helpful in clinical populations who demonstrate limited insight into cognitive deficits and/or experience memory difficulties (e.g., mild cognitive impairment, dementia; Cain, Depp, & Jeste, 2009). In addition, the data can be captured in the participant's natural environment without drastically changing or influencing his or her daily routine (Jones & Johnston, 2011). Thus, adding an EMA to assessment protocols may assist neuropsychologists in identifying fluctuations in cognitive abilities over time, as well as the relationship of subjective experiences (e.g., mood, pain) on cognitive functioning.

Final Remarks and Recommendations

As we have reviewed the latest progress in technology use in neuropsychological assessment, there are several general conclusions to be made. First, studies generally support the psychometric properties of computerized testing and suggest that these administrations

are not inferior to traditional paper and pencil tests. In addition, using computers to obtain supplemental cognitive and behavioral information about performance could result in more comprehensive evaluations of neurological functioning. Thus, it is recommended that new assessments consider embedded measures of cognitive abilities that are challenging to measure with traditional paper and pencil-based administrations but may be informative for diagnosis and treatment, such as approach to testing, response latencies, and/or task planning.

Virtual reality technology offers a unique opportunity to gain perspective on IADL performance of real-world scenarios in a safe and controlled environment. The types of scenarios are endless, as developers can create tasks that mimic those of everyday life, including grocery shopping, driving, or cooking. In addition, experimenter-controlled distractions and interruptions can provide valuable information about how performance is affected by everyday disruptions. These adaptations are more representative of real-world tasks in which cognitive demands are rarely carried out in a vacuum. Thus, the utility of virtual reality, even with its limitations, has yet to be realized in the field of neuropsychology. It is recommended that continued research investigates the relationships of virtual reality with real-world performance so that improvements to assessments can be made.

More recent focus has been placed on the evaluation of everyday functioning, above and beyond the theoretical relationships between neuropsychological tests and IADL performance. This has placed a strain on the field to develop more accurate and ecologically valid measures of everyday abilities. The current reliance on self-report measures for IADL performance poses limitations, as it is well established that self-report of IADL performance is subject to personal biases and the influence of cognitive awareness (Dassel & Schmitt, 2008; Suchy et al., 2010; Suchy, Kraybill & Franchow, 2011). Using smart environment “laboratories” in which participants complete scripted everyday tasks, neuropsychologists may gain a better understanding of relationships between performances on traditional tests of cognition and IADLs, which could better inform treatment recommendations and test development. Furthermore, collecting real-time data through EMA approaches could shed light on relationships between subjective experiences and cognition, as well as the influence of cognitive abilities on daily tasks. Complementing the collection of EMA data, continuous activity monitoring through smart environments may also be useful in understanding relationships between self-reported measures of functioning (e.g., EMA) and non-invasive sensors data that represents activity in the home. Thus, having individuals live in a smart environment and simultaneously participating in EMA data collection could provide a valuable dataset for investigating the relationship between self-reported and actual performance of IADLs. Connections between everyday functioning and cognitive abilities could further the development of effective monitoring and treatment options for individuals at risk or currently diagnosed with neurological disorders (Kaye, 2008).

Technology is continuing to grow, and with every new electronic gadget our society experiences a shift in new knowledge, novel application of information, and even development of new associated skills. With these transformations come challenges for the field of neuropsychology. Neuropsychological assessment is strained to maintain pace with the latest technology and determine how these advances influence human cognition. Thus, neuropsychologists should continue to make strides in researching new ways to assess cognitive and functional abilities in order to provide quality assessment and care for future generations of clients.

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Table 1

Search Terms for Literature Review: PsycInfo, PubMed, IEEE Xplore

Modality / Sub Category	Search Terms
Computer-Based Assessment	cognit* OR memory OR executive OR attention OR processing speed OR iadl OR adl OR daily living OR daily skills OR everyday function* AND (comput* OR technolog*)
Virtual Reality	cognit* OR memory OR executive OR attention OR processing speed OR iadl or adl OR daily living OR daily skills OR everyday function* OR gait* OR fall* risk OR fall detect* AND (virtual* OR three-dimension* OR 3D OR immers*)

Table 2

Studies of Individual Computer-Based Neuropsychological Tests

Authors	Participants	Assessments	Administration Modalities	Additional Variables Assessed	Findings & Advantages	Disadvantages & Author Critiques
Guevara et al. (2009)	None. Overview of test protocol for computer administration.	HANOIPC3 (computer version of Tower of Hanoi)	Computer		Customized modification of rules, on-line feedback, time-stamped latencies for moves.	Only one level of difficulty (but can be manipulated by administrator)
Mataix-Cols & Bartres-Faz (2002)	43 healthy young adults, (mean age 22.5; no range reported)	Tower of Hanoi	Manual and Computer	Gender	No differences in administration modality. Computer version may result in fewer scoring errors on a complex test.	Participants were university students with computer experience. Age and computer use effects should be addressed.
Noyes & Gariand (2003)	3 studies; 39, 76, and 56 healthy young adults (age 18-23.58)	Tower of Hanoi	Manual, Computer, and Mental Representation		Computer version revealed better overall scores, more moves needed, and longer time for completion.	Computer may reduce participant effort and increase trial-and-error.
Williams & Noyes (2007)	60 healthy younger adults, (age 20.08-35.58)	Tower of Hanoi	Manual, Computer, and Mental Representation		No significant differences in administration modality.	Computer version may reduce load on working memory.
Salnaitis et al. (2011)	83 adults with low, moderate, and high levels of psychopathic tendencies (age 18-54)	Tower of Hanoi	Manual and Computer	Psychopathy, Impulse response styles, Gender	Impulsive response style was associated with poorer performance on computer but not manual version.	Need for additional norms for computerized version, rather than comparing results to manual administration norms.
Tien et al. (1996)	33 adults with psychiatric disorders (age 17-66)	WCST	Manual and Computer		More total errors and non-persistent errors on computer version. No differences on perseverative errors/responses, or categories.	Computer version allows for reliable scoring, administration, concentration on behavioral observations during task.
Feldstein et al. (1999)	22 healthy young adults for each of 5 conditions (mean age 24.88-29.40) mean age 28.64	WCST	Manual and 4 Computer versions		Normative differences between manual and computer versions.	Norms specific to computer version are needed.
Elkind et al. (2001)	63 healthy adults (age 18-74)	WCST, Look for a Match (LFAM) Virtual Reality WCST	Computer, Virtual Reality		VR LFAM was more difficult but reportedly more enjoyable than computer WCST.	VR may increase interest and effort, suggesting more accurate findings.
Steinmetz et al. (2010)	100 healthy adults (age 18-58)	WCST	Manual and Computer		Computer version produced larger variances for total errors, perseverative errors, and failure to maintain set.	Computer and manual versions cannot be used interchangeably with the same norms.
Edwards et al. (1996)	3 studies, 20, 27, and 60 healthy adults (age 18-41)	Stroop	Manual and Computer	Caffeine	Faster responses over trials in computer version.	Computer and manual versions may not be

Authors	Participants	Assessments	Administration Modalities	Additional Variables Assessed	Findings & Advantages	Disadvantages & Author Critiques
Parsons et al. (2011)	20 healthy young adults (age not reported)	Stroop	Manual, Computer (ANAM), & Virtual Reality	Low- and High-threat stimuli in VR environment	VR task more sensitive to reaction time and inhibition measures.	analogous and require separate norms. May be useful to test executive abilities and interference from external stimuli.

Note. ANAM = Automated Neuropsychological Assessment Metrics; WCST = Wisconsin Card Sorting Test; VR = Virtual Reality.

Table 3

Studies of Computer-Based Neuropsychological Test Batteries

Battery Name	Normal Aging	Mild Cognitive Impairment	Alzheimer's Disease & Dementia	Parkinson's Disease	Head Injury	Other
ANAM	Repeated assessments in military populations are necessary to establish stable performance (Eonta et al., 2011). Normative data for assessment of TBI in military population (Vincent et al., 2012).		100% classification compared to healthy older adults (Levinson et al., 2005).	Variable subtest reliability but high global changes in PD (Hawkins et al., 2012). Differentiation between impaired PD and controls (Kane et al., 2007).	Strong construct validity demonstrated in TBI population (Bleiberg et al., 2000). Erratic and inconsistent stability in performance within- and across-days compared to controls (Bleiberg et al., 1997). Sensitive to improvements in cognition post-concussion (Daniel et al. 1999). 91.6% classification rate for TBI versus controls (Levinson & Reeves, 1997). Poorer performance in TBI compared to controls (Bryan & Hernandez, 2012). No relationship between number of lifetime TBIs and ANAM performance (Ivins et al., 2009).	
CANTAB	Overall performance declined with age and IQ (Robbins et al., 1994). Practice effects present in healthy elderly (Lowe & Rabbitt, 1998). Paired associates learning and spatial recognition subtests distinguished pre-clinical memory deficits from healthy controls (de Jager & Budge, 2005). Sensitive to executive function deficits in normal aging (Robbins et al., 1998).	Paired associate learning subtest was sensitive to amnesic MCI (Junkkila et al., 2012; Egerhazi et al., 2007).	Longitudinal assessment with CANTAB differentiated early stages of dementia from controls (Fowler et al., 2002). Paired associate learning subtest was sensitive to Alzheimer's disease (Egerhazi et al., 2007; O'Connell et al., 2004; Sahgal et al., 1991). Visual-spatial and visual memory impairments could distinguish stages of AD (Sahakian et al., 1988; Sahgal et al., 1991). Memory impairment without attentional deficits	Tower subtest was sensitive to cognitive deficits in PD (McKinlay et al., 2009), including planning time and spatial working memory (Morris et al., 1988). Visual search and set-shifting deficits in PD patients (Downes et al., 1989).	ADHD: Significantly more impairment in ADHD than controls (Fried et al., 2012; Gau & Shang, 2010). Used widely to assess executive functioning skills in ADHD and effects of medication on symptoms (see review in Chamberlain et al., 2011).	

Battery Name	Normal Aging	Mild Cognitive Impairment	Alzheimer's Disease & Dementia	Parkinson's Disease	Head Injury	Other
CAMCOG	Assessments with the CAMCOG were not as sensitive to mild memory problems compared to CANTAB (de Jager & Budge, 2005). Useful screening tool for populations with low-education (Aprahamian et al., 2011a).	Language, Memory, Praxis, and Calculation subscales were sensitive to MCI (Aprahamian et al., 2011b). Reduced version of CAMCOG was sensitive to MCI (Aprahamian et al., 2011b).	Sensitive as an initial screening of cognitive deficits in Alzheimer's disease (Heinik et al., 2004). Orientations and Memory subscales were sensitive to AD deficits and conversion from MCI to AD (Conde-Sala et al., 2012). Total scores sensitive to conversion from MCI to dementia (Gallagher et al., 2010). Distinguished MCI from dementia (Nunes et al., 2008).	Decline in performance over 13-month period (Athey & Walker, 2006). Sensitive to previously undetected cognitive deficits in PD (Athey et al., 2005; Hobson & Meara, 1999).		Stroke: CAMCOG-R is comparable to detection of cognitive deficits in stroke patients (de Winkel-Witfox et al., 2008; Leeds et al., 2001). CAMCOG-R demonstrated 83% sensitivity to post-stroke dementia (de Koning et al., 2005).
CNS Vital Signs	Test-retest reliability and normative data for decades of normal aging (Gualtieri & Johnson, 2005).	Distinguished MCI from normal aging (Gualtieri & Johnson, 2005).	Distinguished dementia from mild cognitive impairment on subscales of memory, processing speed, and cognitive flexibility (Gualtieri & Johnson, 2005).		Subscales of psychomotor speed and cognitive flexibility were most sensitive to severity level of TBI (Gualtieri & Johnson, 2008). Good discriminant validity for post-concussion and severe TBI (Gualtieri & Johnson, 2006).	ADHD: Good discriminant validity for both treated and untreated ADHD symptoms (Gualtieri & Johnson, 2006).
CogState	Effective test-retest reliability for monitoring mild decline in normal aging over 12-month period (Darby et al., 2012). Stability in performance over 12 months (Fredrickson, 2010). Practice effects were most significant between 1st and 2nd administrations in one day (Collie et al., 2003). Practice effects were present at one-week follow-up but were significantly reduced after one month (Falletti et al., 2006). Factor analysis for performance stability on GMLT subscale (Pietrzak et al., 2008). Decline in performance associated with amount of cerebral amyloid in	Continuous Paired Associate Learning was sensitive to amnesic MCI (Harel et al., 2011). Working and delayed memory were most impaired for MCI (Lim et al., 2012). Continuous learning task performance significantly declined for amnesic MCI participants over 12 months (Maruff et al., 2004). Multiple administrations in one day reliably	Distinguished from healthy older adults by 3 rd and 4 th administration in 3-hour span (Darby et al., 2011). Minimal practice effects (Hammers et al., 2011). Inability to distinguish		Development of criterion validity measures for mild	ADHD: Differentiated from healthy controls (Yamashita et al., 2011) Stroke: Detection and Identification task performance 2 weeks after stroke was related to 3-month follow-up

Battery Name	Normal Aging	Mild Cognitive Impairment	Alzheimer's Disease & Dementia	Parkinson's Disease	Head Injury	Other
Mindstreams	non-demented older adults (Darby et al., 2011). Participant and administrator feedback for older adult samples (Fillit et al., 2008).	distinguished MCI from healthy older adults (Darby et al., 2002). MCI performed more poorly than older adult controls (Doniger et al., 2005, 2006, 2009; Dwolatzky et al., 2003, 2004; Osher et al., 2011).	different dementia types (Hammers et al., 2012). Distinguished from healthy older adults (Dwolatzky et al., 2010) and MCI (Doniger, 2006; Dwolatzky et al., 2004).	Mild dementia and MCI discrimination (Doniger et al., 2005). Distinguished by severity on CDR assessment (Dwolatzky et al., 2010).	head injury (Maruff et al., 2009).	testing (Cumming et al., 2012). ADHD: Increased problems with sustained attention in ADHD relative to controls (Schweiger et al., 2007).

Note. ANAM = Automated Neuropsychological Assessment Metrics; CANTAB = Cambridge Neuropsychological Test Automated Battery; CAMCOG = Cambridge Cognition Examination; CAMCOG-R = Cambridge Cognition Assessment – Revised; CDR = Clinical Dementia Rating; MCI = Mild Cognitive Impairment; ADHD = Attention-Deficit/Hyperactivity Disorder

Table 4

Virtual Reality Based Neuropsychological Assessments

Assessment	VR Task Environment & Level of Immersion	Cognitive Variables Assessed	Everyday Functioning Variables Assessed	Clinical Populations Assessed
"Look for a Match" Based on WCST (Elkind et al., 2001)	Beach scene. 3D Computer simulation with stereographic eyewear.	Executive functioning	Interference from external stimuli.	Healthy young adults (Elkind et al., 2001)
Virtual Reality Stroop Task (Parsons et al., 2011)	Military Humvee. 3D Computer simulation with head-mounted display and steering wheel.	Executive functioning, reaction/ response time	Cognitive interference from driving and physiological response to high/low threat conditions.	TBI and healthy controls (Parsons et al., 2011)
Virtual Reality Paced Serial Assessment Test (Parsons et al., 2012)	Middle Eastern city and military "check point". 3D Computer simulation with head-mounted display.	Processing speed, attention, mathematical processing, reaction time	Cognitive interference in high and low stress scenarios, and environmental distractions.	TBI and healthy controls (Parsons et al., 2012)
Virtual Reality Cognitive Performance Assessment Test (Parsons et al., 2008)	City scene. 3D Computer simulation with head-mounted display.	Verbal and visual learning and memory	Cognitive interference by environmental distractions.	Healthy younger adults, age 21-36 (Parsons & Rizzo, 2008)
Virtual Classroom (Rizzo et al., 2006)	Elementary classroom. 3D Computer simulation with head-mounted display.	Attention, language (Boston Naming Test), executive functioning (Stroop)	Classroom demands of children. Cognitive interference and distractibility (head tracking) from environmental stimuli.	ADHD and healthy controls (Adams et al., 2009; Parsons et al., 2007)
Virtual Errands Test (McGeorge et al., 2001)	Supermarket. 3D Computer simulation.	Memory, attention, executive functioning, planning, organization, multi-tasking	Shopping and planning. Cognitive interference and distractibility from environmental stimuli.	Autism spectrum (Rajendran et al., 2011); healthy young adults (Law et al., 2006)
Virtual Multiple Errands Test (Rand et al., 2009)	Food market and supermarket. 3D Computer simulation.	Memory, attention, visuospatial skills, executive functioning, planning, organization, multi-tasking	Shopping, planning, driving. Cognitive interference and distractibility from environmental stimuli.	Stroke (Rand et al., 2009; Raspelli et al., 2011). Parkinson's disease (Albani et al., 2010, 2011)
Virtual kitchen (Zhang et al., 2001)	Kitchen. 3D Computer simulation.	IQ (WAIS-R), attention, memory, executive functioning	Meal preparation: accuracy, sequencing, total time, assistance needed.	TBI (Zhang et al., 2001; 2003)

Note. ADHD = Attention Deficit/Hyperactivity Disorder, TBI = Traumatic Brain Injury; WAIS-R = Wechsler Adult Intelligence Scale – Revised.