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Validation of the Virtual Reality Everyday Assessment Lab (VR-EAL): An Immersive Virtual Reality Neuropsychological Battery with Enhanced Ecological Validity

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Abstract

Objective: The assessment of cognitive functions such as prospective memory, episodic memory, attention, and executive functions benefits from an ecologically valid approach to better understand how performance outcomes generalize to everyday life. Immersive virtual reality (VR) is considered capable of simulating real-life situations to enhance ecological validity. The present study attempted to validate the Virtual Reality Everyday Assessment Lab (VR-EAL), an immersive VR neuropsychological battery, against an extensive paper-and-pencil neuropsychological battery. **Methods:** Forty-one participants (21 females) were recruited: 18 gamers and 23 non-gamers who attended both an immersive VR and a paper-and-pencil testing session. Bayesian Pearson’s correlation analyses were conducted to assess construct and convergent validity of the VR-EAL. Bayesian *t*-tests were performed to compare VR and paper-and-pencil testing in terms of administration time, similarity to real-life tasks (i.e., ecological validity), and pleasantness. **Results:** VR-EAL scores were significantly correlated with their equivalent scores on the paper-and-pencil tests. The participants’ reports indicated that the VR-EAL tasks were significantly more ecologically valid and pleasant than the paper-and-pencil neuropsychological battery. The VR-EAL battery also had a shorter administration time. **Conclusion:** The VR-EAL appears as an effective neuropsychological tool for the assessment of everyday cognitive functions, which has enhanced ecological validity, a highly pleasant testing experience, and does not induce cybersickness.

Keywords: Prospective memory, Episodic memory, Attention, Executive function, Everyday functioning, Virtual reality

INTRODUCTION

The ability to perform activities in everyday life is dependent upon cognitive abilities such as attention, episodic memory, executive abilities, and prospective memory (Mlinac & Feng, 2016). The neuropsychological assessment of these cognitive abilities benefits from an ecologically valid approach to better understand the quality of an individual’s everyday functioning (Chaytor & Schmitter-Edgecombe, 2003). Ecological validity increases the probability that an individual’s cognitive performance will replicate how they will respond in real-life situations (Bailey, Henry, Rendell, Phillips, & Kliegel, 2010; Burgess et al., 2006; Chaytor & Schmitter-Edgecombe, 2003).

Verisimilitude and veridicality are the two predominant approaches for achieving the ecological validity of neuropsychological tests (Franzen & Wilhelm, 1996; Chaytor & Schmitter-Edgecombe, 2003; Spooner & Pachana, 2006). Verisimilitude refers to the level of resemblance to the complexity and cognitive demands of everyday tasks by the neuropsychological tests (Franzen & Wilhelm, 1996; Chaytor & Schmitter-Edgecombe, 2003; Spooner & Pachana, 2006). Veridicality refers to the strength of the relationship between the outcomes of neuropsychological tests and everyday functioning measures (e.g., questionnaires pertinent to everyday functioning and independence; Franzen & Wilhelm, 1996; Chaytor & Schmitter-Edgecombe, 2003; Spooner & Pachana, 2006). While both verisimilitude and veridicality approaches have their merits, the literature suggests that the verisimilitude approach may be better predictors of real-world memory and attention (Higginson,

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Arnett, & Voss, 2000), executive functioning (e.g., multitasking, planning, and mental flexibility; Burgess, Alderman, Evans, Emslie, & Wilson, 1998), and prospective memory abilities (e.g., remembering to initiate a planned action in the future; Haines et al., 2019; Phillips, Henry, & Martin, 2008) than the veridicality approach (Chaytor & Schmitter-Edgecombe, 2003; Spooner & Pachana, 2006).

Several laboratory-based test batteries that simulate real-life tasks exist in the neuropsychological literature including those assessing attention (e.g., Test of Everyday Attention, TEA; Robertson, Ward, Ridgeway, & Nimmo-Smith, 1994), memory (e.g., Rivermead Behavioral Memory Test-III, RBMT-III; Wilson, Cockburn, & Baddeley, 2008), executive abilities (e.g., Behavioral Assessment of Dysexecutive Syndrome, BADS; Wilson, Alderman, Burgess, Emslie, & Evans, 1996), and prospective memory (e.g., Cambridge Prospective Memory Test, CAMPROMPT; Wilson, 2005). Yet, such neuropsychological test batteries tend to incorporate simple, static stimuli within a highly controlled environment and do not fully resemble the complexity of real-life situations (Parsons, 2015; Rand, Rukan, Weiss, & Katz, 2009). Attempts to provide better assessments of everyday abilities have involved assessments in real-life settings such as performing errands in a shopping center or a pedestrianized street (e.g., Garden, Phillips, & MacPherson, 2001; Shallice & Burgess, 1991). However, these cannot be standardized for use in other clinics or laboratories, they may not be feasible for some individuals in challenging populations (e.g., psychiatric patients, stroke patients with paresis or paralysis), they are time-consuming and expensive, they require participant transport and consent from local businesses, and they lack experimental control over the external situation (e.g., Elkind, Rubin, Rosenthal, Skoff, & Prather, 2001; Logie, Trawley, & Law, 2011; Parsons, 2015; Rand et al., 2009).

The use of technology such as video recordings of real-world locations and non-immersive virtual environments (Farrimond, Knight, & Titov, 2006; McGeorge et al., 2001; Paraskevaides et al., 2010) have also been considered to simulate real-life situations. Non-immersive virtual reality (VR) tests such as the Edinburgh Virtual Errands Test (Logie et al., 2011), the Jansari Assessment of Executive Function (Jansari et al., 2014), the Virtual Multiple Errands Test within the Virtual Mall (Rand et al., 2009), and the Virtual Reality Shopping Task (Canty et al., 2014) attempt to simulate real-life tasks and are considered more cost-effective, require less administration time, have greater experimental control, and can be easily be adapted for other clinical or research settings (Parsons, McMahan, & Kane, 2018; Werner & Korczyn, 2012; Zygouris & Tsolaki, 2015). Non-immersive VR tests can also offer automated scoring and standardized administration, enabling clinicians and researchers to administer these tests with only limited training. Finally, some non-immersive VR tests also offer shorter versions of the test that focus on the assessment of specific cognitive functions (Parsons et al., 2018; Werner & Korczyn, 2012; Zygouris & Tsolaki, 2015).

However, the user interface and procedure of non-immersive VR tests can be challenging for individuals without gaming backgrounds (Parsons et al., 2018; Zaidi, Duthie, Carr, & Maksoud, 2018), especially for older adults and clinical populations such as individuals with mild cognitive impairment or Alzheimer's disease (Werner & Korczyn, 2012; Zygouris & Tsolaki, 2015). Immersive VR tests, which share the same advantages as non-immersive ones, may overcome these challenges (Rizzo, Schultheis, Kerns, & Mateer, 2004; Bohil, Alicea, & Biocca, 2011; Parsons, 2015; Teo et al., 2016). In addition, individuals without gaming experience have been found to perform better in immersive VR environments due to the first-person perspective and ergonomic/naturalistic interactions that are proximal to real-life actions (Zaidi et al., 2018). Also, while VR tests have in the past resulted in VR-induced symptoms and effects (VRISE) such as nausea, dizziness, disorientation, fatigue, or instability (Bohil et al., 2011; de Franca & Soares, 2017; Palmisano, Mursic, & Kim, 2017), which compromise neuropsychological (Mittelstaedt, Wacker, & Stelling, 2019; Nalivaiko, Davis, Blackmore, Vakulin, & Nesbitt, 2015; Nesbitt, Davis, Blackmore, & Nalivaiko, 2017) and neuroimaging data (Arafat, Ferdous, & Quarles, 2018; Gavgani et al., 2018; Toschi et al., 2017), certain contemporary VR head-mounted displays (HMDs) and VR software with naturalistic and ergonomic interactions and navigation within the virtual environment reduce or show no symptoms of VRISE (see Kourtesis, Collina, Doumas, & MacPherson, 2019a). Lastly, immersive VR has been found to provide deeper immersion in the virtual environment than non-immersive VR; deeper immersion has been found to induce substantially less adverse VRISE (Kourtesis, Collina, Doumas, & MacPherson, 2019b; Weech, Kenny, & Barnett-Cowan, 2019).

We recently developed the Virtual Reality Everyday Assessment Lab (VR-EAL) to create an immersive virtual environment that simulates everyday tasks proximal to real life to assess prospective memory, episodic memory (immediate and delayed recognition), executive functions (i.e., multitasking and planning), and selective visual, visuospatial, and auditory attention (Kourtesis, Korre, Collina, Doumas, & MacPherson, 2020). In the VR-EAL, individuals are exposed to alternating tutorials (practice trials) and storyline tasks (assessments) to allow them to become familiarized with both the immersive VR technology and the specific controls and procedures of each VR-EAL task. Moreover, VR-EAL offers also a shorter version (i.e., scenario) where only episodic memory, executive function, selective visual attention, and selective visuospatial attention are assessed. Also, the examiner can opt to simply assess a specific cognitive function, where the examinee will go through the generic tutorial, the specific tutorial for this task, and the storyline task that assess the chosen cognitive function (e.g., selective visual attention).

VR-EAL endeavors to be the first immersive VR neuropsychological battery of everyday cognitive functions. Our previous work has shown that the VR-EAL does not induce VRISE (Kourtesis et al., 2020). However, we have yet to

demonstrate the validity of the VR-EAL as a neuropsychological tool. In the current study, the full version of the VR-EAL was administered to participants and compared with the existing paper-and-pencil neuropsychological tests to assess the construct validity of the VR-EAL. We also aimed to replicate our previous findings that the VR-EAL does not induce VRISE, using the Virtual Reality Neuroscience Questionnaire (VRNQ; Kourtesis et al., 2019b). Finally, comparisons between the VR-EAL and neuropsychological paper-and-pencil tests were conducted in terms of verisimilitude (i.e., ecological validity), pleasantness, and administration time.

METHODS

Participants

Participants were recruited *via* social media and the internal mailing list of the University of Edinburgh. Forty-one participants (21 females) aged between 18 and 45 years ($M = 29.15$, $SD = 5.80$) were recruited: 18 considered themselves to be gamers (7 females) and 23 (14 females) considered themselves to be non-gamers. The mean education of the group was 13.80 years ($SD = 2.36$, range = 10–16). The study was approved by the Philosophy, Psychology and Language Sciences Research Ethics Committee of the University of Edinburgh. Written informed consent was obtained from each participant. All participants received verbal and written instructions regarding the procedures, possible adverse effects of immersive VR (e.g., VRISE), utilization of the data, and general aims of the study.

Materials

Hardware

An HTC Vive HMD with two lighthouse stations for motion tracking and two HTC Vive wands with six degrees of freedom (6DoF) for navigation and interactions within the virtual environment was implemented in accordance with our previously published technological recommendations for immersive VR research (Kourtesis et al., 2019a). The spatialized (bi-aural) audio was facilitated by a pair of Senhai Kotion Each G9000 headphones. The size of the VR area was 5 m², which facilitates an adequate space for immersion and naturalistic interaction within virtual environments (Borrego, Latorre, Alcañiz, & Llorens, 2018). The HMD was connected to a laptop with an Intel Core i7 7700HQ 2.80 GHz processor, 16 GB RAM, a 4095 MB NVIDIA GeForce GTX 1070 graphics card, a 931 GB TOSHIBA MQ01ABD100 (SATA) hard disk, and Realtek High Definition Audio.

VR-EAL

VR-EAL attempts to assess everyday cognitive functioning by assessing prospective memory, episodic memory (i.e., immediate and delayed recognition), executive functioning (i.e., planning, multitasking), and selective visual,

visuospatial, and auditory (bi-aural) attention within a realistic immersive VR scenario lasting around 60 min (Kourtesis et al., 2020). See Table 1 and Figures 1 and 2 for a summary of the VR-EAL tasks assessing each cognitive ability. See Table 2 for the description of the VR-EAL tasks and Table 3 for the administration procedures and scoring of the VR-EAL tasks. For a full description of the VR-EAL's scenarios, tasks, and scoring, see Kourtesis et al. (2020). Also, a brief video recording of the VR-EAL may be accessed at this hyperlink: <https://www.youtube.com/watch?v=IHEIvS37Xy8&t=>.

Paper-and-Pencil Tests

Established ecologically valid paper-and-pencil test batteries in terms of both verisimilitude and veridicality were selected to match the equivalent VR-EAL tasks and examine their ecological and construct validity (i.e., CAMPROMPT, RBMT-III, BADS, and TEA). Two additional neuropsychological tests that are ecologically valid in terms of only veridicality were also included to assess the validity of the VR-EAL's visuospatial attention and multitasking tasks. Tests of visuospatial attention and multitasking that are ecologically valid both in terms of verisimilitude and veridicality are not available in the literature.

Prospective memory. The CAMPROMPT was administered to evaluate prospective memory using six prospective memory tasks (Wilson, 2005). Three tasks are event-based and three are time-based. The participant is required to perform several distractor tasks (e.g., word-finder puzzles and general knowledge quizzes and questions) for 20 min, as well as remember to perform the prospective memory tasks (e.g., when the participant faces a question which includes the word "EastEnders," s/he needs to give a book to the examiner). The utilization of reminding strategies (e.g., taking notes) is permitted to aid the participant to remember when and how to perform the prospective memory tasks. The CAMPROMPT provides three scores: a total score (out of 36), an event-based score (out of 18), and a time-based score (out of 18).

Episodic memory. Two subtests from the RBMT-III (Wilson et al., 2008) were administered to assess episodic memory. The recall tasks were opted since they offer two scores (immediate recall and delayed recall), while the recognition tasks provide a score only for delayed recognition. The immediate and delayed story recall tasks were used to match the VR-EAL's immediate and delayed recognition tasks. The participant listens to a story from a newspaper read aloud by the examiner. The participant should recall the story immediately (immediate recall out of 21) and after approximately 20 min (delayed recall out of 21).

Executive function: planning. The Key Search task from the BADS (Wilson et al., 1996) was utilized as a test of planning (Wilson, Evans, Emslie, Alderman, & Burgess, 1998). While the Key Search task assesses planning ability, it also involves

Table 1. VR-EAL tasks and score ranges

Scene	Cognitive function	Task	Score ranges
3	Prospective memory	Write down the notes for the errands.	0–6
3	Immediate recognition	Recognizing items on the shopping list.	0–20
3	Planning	Drawing the route to be taken.	0–19
6	Multitasking	Cooking task (preparing breakfast).	0–16
6	Prospective memory – event-based	Take medication after breakfast.	0–6
8	Selective visuospatial attention	Collect items from the living room.	0–20
8	Prospective memory – event-based	Take the chocolate pie out of the oven.	0–6
10	Prospective memory – time-based	Call Rose at 10 am.	0–6
12	Selective visual attention	Find posters on both sides of the road.	0–16
14	Delayed recognition	Recognizing items from the shopping list.	0–20
15	Prospective memory – time-based	Collect the carrot cake from the bakery at 12 pm.	0–6
16	Prospective memory – event-based	False prompt before going to the library.	-6–0
17	Prospective memory – event-based	Return the red book to the library.	0–6
19	Selective auditory attention	Detect sounds from both sides of the road.	0–32
20	Prospective memory – time-based	False prompt before going back home.	-6–0
21	Prospective memory – event-based	Back home, give the extra pair of keys to Alex.	0–6
22	Prospective memory – time-based	Take the medication at 1 pm.	0–6

*The tasks are presented in the same order as they are performed within the scenario.

other aspects of executive function (e.g., problem-solving and monitoring of behavior; Wilson et al., 1998). The participant should draw his or her route to find lost keys in a field. The quality of the route (e.g., whether it covers the whole field) and the time taken to draw it are considered in the scoring (max score = 16).

Executive functioning. The Color Trails Test (CTT; D’Elia, Satz, Uchiyama, & White, 1996) was administered to assess processing speed and executive functioning. CTT is a non-alphabetical adaptation (i.e., colors and numbers) of the Trail Making Test (Reitan & Wolfson, 1993). CTT has two tasks (i.e., CTT-1 and CTT-2), where the participant must draw a line to connect consecutive numbers. In CTT-1, the numbers in the sequence are in a single color. Comparable to the TMT-A (Reitan & Wolfson, 1993), CTT-1 assesses processing speed. In CTT-2, the numbers are displayed in two colors and the examinee alternates between the two colors for each number in the sequence. Comparable to the TMT-B (Reitan & Wolfson, 1993), CTT-2 assesses task-switching, as well as inhibition and visual attention (D’Elia et al., 1996). The CTT was chosen to assess the validity of the VR-EAL’s multitasking task, and these aspects of executive functioning have been found central in everyday multitasking (Logie et al., 2011). Furthermore, the time to complete in seconds is taken as the score for CTT-1 and CTT-2, and the difference between the two scores (i.e., CTT-2 minus CTT-1) is considered an index of executive function.

Selective visual attention. The Ruff 2 and 7 Selective Attention Test (RSAT; Ruff, Niemann, Allen, Farrow, & Wylie, 1992) was used to assess selective visual attention. The participant is asked to identify target numbers (i.e., 2s and 7s) and ignore the distractors (either numbers

or letters) in the block. The examinee is required to implement two different strategies for each type of block; an automatic selection of 2s and 7s for the blocks with letter-distractors and a controlled detection of 2s and 7s for the blocks with number distractors. The RSAT produces two scores: a detection speed score (out of 80) and a detection accuracy score (out of 59). The scores consider the number of detected 2s and 7s, as well as, the number of misses and errors. The RSAT was opted to match the VR-EAL selective visuospatial attention task because it requires different scanning strategies, shifting of attention to another block, and considers the number of misses and mistakes.

Selective visual attention. The Map task from the TEA (Robertson et al., 1994) was administered to assess selective visual attention (i.e., the ability to detect visual targets, while disregarding similar visual distractors). The participant should find as many as possible restaurant symbols (version A) or gas station symbols (version B) on a map of Philadelphia (USA) within 2 min. The total score out of 80 corresponds to the number of symbols detected overall, while one subscore corresponds to the number of symbols found in the first minute, and the other subscore refers to the number of symbols detected in the second minute.

Selective auditory attention. The Elevator Counting with Distraction task of the TEA (Robertson et al., 1994) was administered, which measures auditory selective attention (i.e., the ability to select target sounds, while ignoring competitive auditory distractors). In each trial, the participant listens to different sounds (beeps), where s/he needs to count the number of normal pitched beeps (i.e., targets) and disregard the high-pitched and low-pitched beeps (i.e., distractors). The total score is the number of correct responses across the 10 trials (max score = 10).

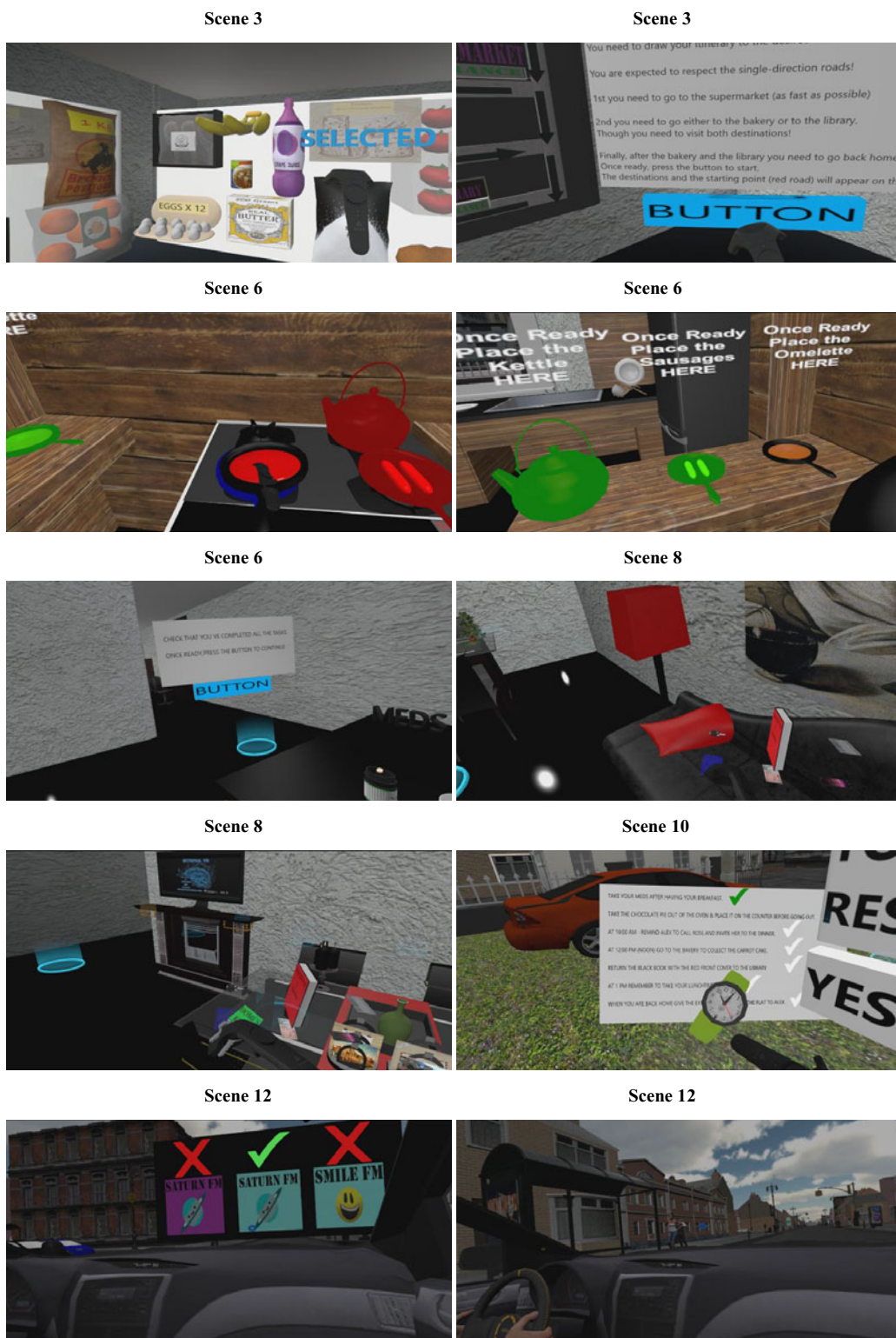


Fig. 1. VR-EAL Storyline: Scenes 3–12. Derived from Kourtesis et al. (2020).

Questionnaires. Questionnaires were administered to examine the VR software quality and VRISE, gaming experience of the participants, as well as the verisimilitude and pleasantness of the tests. See Table 4 for a description of the questionnaires.

Procedure

Participants individually attended both the VR session and the paper-and-pencil session; the order was pseudorandomized across participants. In the VR session, participants

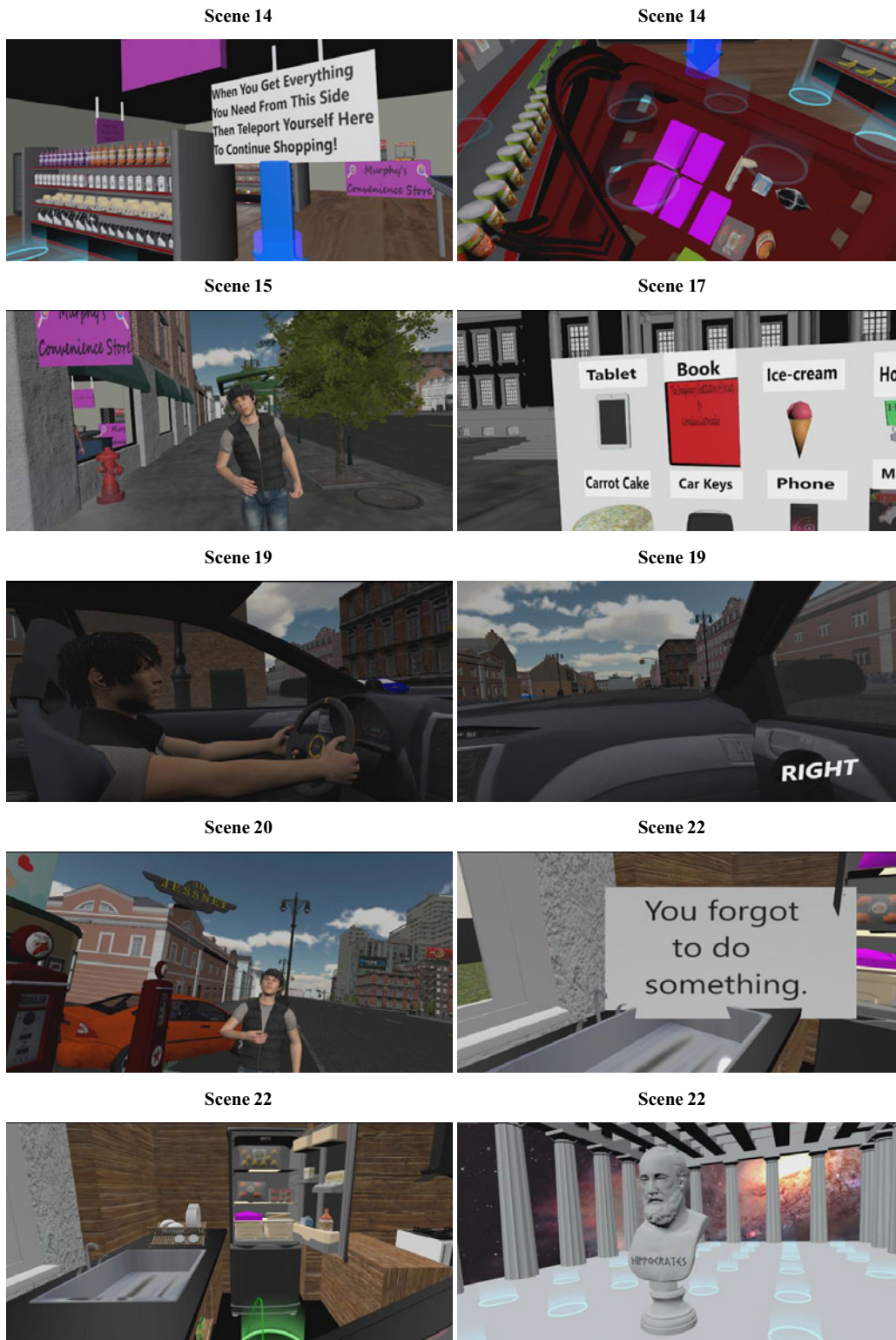


Fig. 2. VR-EAL Storyline: Scenes 14–22.
Derived from Kourttesis et al. (2020).

participated in an induction session to introduce them to the HMD and controllers (i.e., HTC Vive and 6DoF wands — controllers) prior to immersion. After completion of VR-EAL, participants completed the VRNQ and the VR versions of the comparison questionnaire (i.e., to assess pleasantness

and verisimilitude). During the paper-and-pencil session, participants completed the paper-and-pencil comparison questionnaires (i.e., pleasantness and verisimilitude) after each test. The duration of each session was timed using a stopwatch.

Table 2. VR-EAL tasks' description

Cognitive function	Description
Episodic memory	Both immediate and delayed episodic memory is assessed. First, the participant needs to memorize a shopping list that is presented audio-visually. Immediately after the presentation of the list, the participant is presented with 30 items and should visually recognize and select the 10 items from the shopping list (immediate recognition). Participants are then expected to choose the items from the list when they arrive at the supermarket approximately 20 min later (delayed recognition).
Executive function: planning	Planning ability is assessed by asking the participant to draw his or her route around the city (e.g., visiting the bakery, supermarket, library, and returning home) on a 3D interactive board.
Executive function: multitasking	Multitasking is examined using a cooking task, where the participant should prepare and serve his or her breakfast (e.g., sausages, omelet, and a cup of tea/coffee) and place a chocolate pie in the oven.
Prospective memory	Comparable to the CAMPROMPT, VR-EAL considers both event-based and time-based prospective memory tasks. In the event-based tasks, the participant should remember to perform a prospective memory action when a particular event occurs (e.g., take medicines after breakfast). In the time-based tasks, the examinee should remember to perform a planned action at a specific time (e.g., call Rose at 12 pm).
Visuospatial attention	Visuospatial attention is assessed by asking the participant to find and collect six specific items (i.e., a mobile phone, a £50 note, a library card, the flat keys, a red book, and car keys) in the living room. A reminder of these items remains on the wall (i.e., the items are displayed as 3D objects with labels). However, there are also distractors (i.e., magazines, books, a remote control, a notebook, a pencil, a chessboard, and a bottle of wine) in the room.
Visual attention	Visual attention is measured while the participant is seated as a passenger in a car next to a driver. The participant should identify all the targets (i.e., 16 posters of a radio station) on both sides of the road, while s/he needs to avoid any distractors (i.e., eight posters that are a different shape and eight posters with a different background color).
Auditory attention	Auditory attention is also examined while the participant is seated as a passenger next to a driver. The participant should detect all the target sounds (i.e., 16 bell sounds) presented on both sides of the road, while avoiding the distractor sounds (i.e., eight high pitch bells and eight dongs).

Statistical analyses

A reliability analysis for the VR-EAL was conducted calculating Cronbach's alpha to inspect the internal consistency and reliability of the VR-EAL. A threshold of 0.70–1.00 for Cronbach's alpha was used, which indicates good (i.e., 0.70) to excellent (i.e., 1.00) internal consistency and reliability (Nunally & Bernstein, 1994).

The Bayesian factor (BF_{10}) was used for assessing statistical inference. The BF_{10} threshold ≥ 10 was set for statistical inference in all analyses, which indicates strong evidence in favor of the H1 (Marsman & Wagenmakers, 2017; Rouder & Morey, 2012; Wetzels & Wagenmakers, 2012) and corresponds to a p -value < 0.01 (e.g., $BF_{10} = 10$) (Bland, 2015; Cox & Donnelly, 2011; Held & Ott, 2018). BF_{10} is considered substantially more parsimonious than the p -value in evaluating the evidence against the H0 (Bland, 2015; Cox & Donnelly, 2011; Held & Ott, 2018), especially when evaluating the evidence of H1 against H0 in small sample sizes (Held & Ott, 2018), as in the present study. Notably, BF_{10} allows evidence in either direction (i.e., toward H1 and H0), and its measurement of evidence is insensitive to the stopping rule, which substantially mitigates the issue of multiple comparisons and generates reliable and more generalizable results (Dienes, 2016; Marsman & Wagenmakers, 2017; Wagenmakers et al., 2018).

Bayesian Pearson's correlational analyses were conducted to examine associations between age, years of education, VR experience, gaming experience, and performance on the VR-EAL and paper-and-pencil tasks. Similarly, Bayesian Pearson's correlational analyses were performed to assess construct validity for the entire VR-EAL and convergent validity between the VR-EAL tasks and the paper-and-pencil tasks. Furthermore, Bayesian paired samples t -tests were performed to investigate the differences between VR-EAL and paper-and-pencil tests in terms of verisimilitude, pleasantness, and administration time. Finally, a *post hoc* analyses for the achieved statistical power of the Bayesian Pearson's correlations and Bayesian paired samples t -tests were performed using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007; Faul, Erdfelder, Buchner, & Lang, 2009). All Bayesian analyses were performed using JASP (Version 0.8.1.2) (JASP Team, 2018).

RESULTS

The descriptive statistics of the sample performing the VR-EAL, the paper-and-pencil tests, and questionnaires are displayed in Table 5.

Table 3. VR-EAL task administration and scoring

Task	Scoring
Episodic memory	The user should choose the 10 target items (i.e., create the shopping list) from an extensive array of items, which also contains five qualitative distractors (e.g., semi-skimmed milk vs. skimmed milk), five quantitative distractors (e.g., 1 kg potatoes vs. 2 kg potatoes), and 10 false items (e.g., bread and bananas). The user gains two points for each correctly chosen item, one point for choosing a qualitative or quantitative distractor, and zero points for the false items. Scores range from 0 to 20.
Planning	The road system comprises 23 street units. When the user selects a unit, one point is awarded. The ideal route to visit all three destinations is 15 units; hence, any extra or missing units are subtracted from the total possible score of 15. Up to four more points are awarded for the time taken to complete the task. Scores range from 0 to 19.
Multitasking	Scoring relies on the animations from each game object (i.e., the omelet and the sausages). At the beginning of the animation, both items have a reddish (raw) color which gradually turns to either a yellowish (omelet) or brownish (sausages) color, and finally both turn to black (burnt). The score for each pan hence depends on the time that the user removes the pans from the stove and places them on the kitchen worktop. Equally, the score for boiling the kettle is measured in relation to the stage of the audio playback (e.g., the kettle whistles when the water is ready) that the kettle is placed on the kitchen worktop. Scores range from 0 to 16.
Prospective memory	Example: At the end of a scene, the user should press a button to confirm that all the tasks in the scene are completed. If the user has already taken his/her medication (i.e., prospective memory task) before pressing the final button, then the scene ends, and the user receives six points. Otherwise, the first prompt appears (i.e., “You Have to Do Something Else”). If the user then follows the prompt and takes their medication, they receive four points. If the user presses the final button again, then the second prompt appears (i.e., “You Have to Do Something After Having your Breakfast”). If the user follows this prompt and takes their medication, they receive two points. If the user presses the final button again, then the third prompt appears (i.e., “You Have to Take Your Meds”). If the user follows this prompt and takes their medication, they then receive one point. If the user represses the final button without ever taking their medication, they get zero points, and the scene ends. Scores range from 0 to 6.
Visuospatial attention	The user receives two points for each target item collected (six target items). Also, up to four points are awarded for the speed of detecting the items. If the user attempts to collect one of the distractors, it counts as an error. Up to four points are awarded for the accuracy of detecting items. Scores range from 0 to 20.
Visual attention	The user is awarded one point when a target poster is “spotted” and subtracted one point when a distractor poster is “spotted.” Scores range from 0 to 16.
Auditory attention	Example: If the user presses the trigger on the right controller to detect a target sound originating on the right side (i.e., controller and sound on the same side), then s/he gets two points. If the user presses the trigger on the right controller to detect a target sound originating on the left side (i.e., controller on the opposite side), s/he gains only one point. If the user responds to a distractor sound, irrelevant of its origin or the controller used to respond, one point is deducted. Scores range from 0 to 32.

Note: For all measures, higher scores indicate better performance.

Correlations Between Demographics and Performance

No significant correlations were found between age, education, VR experience, gaming experience, or performance on any of the paper-and-pencil tests or the VR-EAL tasks. The only significant correlations were observed between gaming experience and VR experience, VR experience and the VR session duration, gaming experience and the VR session duration, gaming experience and the duration of the paper-and-pencil testing session, and the duration of the VR session and the paper-and-pencil session (see Table 6).

Convergent and Construct Validity of the VR-EAL

The VR-EAL scores were significantly positively correlated with their equivalent scores on the paper-and-pencil tests (see Table 7). These results support the convergent validity of the

VR-EAL tasks, as well as the construct validity of the VR-EAL as an immersive VR neuropsychological battery. The reliability analysis demonstrated a Cronbach's $\alpha = 0.79$ for VR-EAL, which indicates good internal reliability (Nunally & Bernstein, 1994).

Quality of VR-EAL and VRISE: VRNQ

The median of the VRNQ total score for VR-EAL was 128, which is substantially above the parsimonious cut-off of 120 (maximum score = 140). The medians of the VRNQ domains (i.e., user experience, game mechanics, in-game assistance, and VRISE) were between 31 and 33, again above their respective parsimonious cut-offs of 30 (maximum score = 35). Notably, the medians for all the individual VRISE items (i.e., nausea, dizziness, disorientation, fatigue, and instability) were 7 (i.e., absent feeling), except for fatigue, which was 6 (i.e., very mild feeling). No participant reported a VRISE subscore less than 5 (i.e., mild feeling).

Table 4. Questionnaires' administration and scoring

Evaluation's target	Administration and scoring
VR software quality and VRISE.	The VRNQ was administered to assess the quality of the VR-EAL and the intensity of VRISE. The VRNQ is a 1–7 Likert scale questionnaire comprising 20 questions in total; 5 questions are pertinent to each of the four domains (i.e., user experience, game mechanics, in-game assistance, and VRISE) (Kourtesis et al., 2019b). The assessed VRISE are nausea, dizziness, disorientation, fatigue, and instability. VRNQ produces a total score out of 140 and a subscore out of 35 for each domain. The parsimonious cut-offs of VRNQ were used to assess the suitability of VR-EAL (Kourtesis et al., 2020).
Gaming and VR experience	A survey questionnaire was administered to evaluate the gaming and VR experience of the participants (see Supplementary Material – Figure 1). The questionnaire (Likert scale 1–7) contains two questions regarding the weekly frequency of game playing and VR technology use, and two questions pertinent to the ability to play games and VR technologies use.
Verisimilitude and pleasantness	A comparison questionnaire (two versions; i.e., VR and paper-and-pencil) was administered to examine the participants' views on the pleasantness and ecological validity of the tests performed (see Supplementary Material – Figures 2 and 3). There were two separate versions of the comparison questionnaire with a Likert scale ranging from 1 to 7. There was one version for the VR-EAL tasks (see Supplementary Material – Figure 2), and another for the paper-and-pencil tests (see Supplementary Material – Figure 3). Both versions had the same two questions referring to the level of enjoyment (e.g., 1-highly unpleasant, 7-highly pleasant) and verisimilitude (e.g., 1-totally different from the tasks in daily life, 7-nearly identical to the tasks in daily life) of the tasks. For each version of the questionnaire, the maximum score was 14.

Comparison of the Testing Experience Between VR-EAL and Paper-and-Pencil Tests

The median for enjoyment level was 6 (very pleasant) for the VR-EAL and 5 (pleasant) for the paper-and-pencil assessments (see Figure 3). The median for verisimilitude was 6 (i.e., very similar to everyday life) for VR-EAL, 4 (neither similar nor dissimilar to everyday life) for the ecologically validity tests, and 3 (dissimilar to everyday life) for the remaining paper-and-pencil tests (see Figure 3). The Bayesian *t*-tests demonstrated significant differences between the VR-EAL and paper-and-pencil tests, where the VR-EAL is rated significantly more pleasant and ecologically valid (i.e., verisimilitude) than the paper-and-pencil tests (see Table 8). In addition, the VR session was substantially shorter than the paper-and-pencil session (see Table 8).

DISCUSSION

The VR-EAL was devised to assess cognitive functions (i.e., prospective memory, episodic memory, executive functions, and attentional processes) that are central to everyday functioning. Being an immersive VR research/clinical software, the VR-EAL aims to increase the likelihood that individuals' performance will replicate how they will act in real-life situations (Higginson et al., 2000; Chaytor & Schmitter-Edgecombe, 2003; Phillips et al., 2008; Rosenberg, 2015; Mlinac & Feng, 2016; Haines et al., 2019). In the current study, we attempted to provide convergent, construct, and ecological validity for the VR-EAL tasks. Indeed, we demonstrated that all VR-EAL tasks significantly correlated with their corresponding ecologically valid paper-and-pencil tasks. The VR-EAL also showed good internal consistency, allowing implementation in clinical and research settings

(Nunally & Bernstein, 1994). Therefore, the VR-EAL appears to be an effective, reliable, and ecologically valid tool for the assessment of everyday cognitive functioning, which can be used for clinical and research purposes. Importantly, the VR-EAL is a highly immersive and ergonomic VR neuropsychological battery; immersive VR provides a more ecological valid experience than non-immersive VR (Weech, Kenny, & Barnett-Cowan, 2019) and ergonomic interactions benefit non-gamers as their performance is comparable to gamers (Zaidi et al., 2018).

Notably, the paper-and-pencil tests utilized in this study have been found to be ecologically valid in terms of both verisimilitude and veridicality (or veridicality only), evidencing their ability to predict everyday functioning. For example, the RBMT was highly accurate in predicting the everyday memory functionality of patients with traumatic brain injuries (TBI; Makatura, Lam, Leahy, Castillo, & Kalpakjian, 1999). Also, the RBMT has been strongly associated with occupational therapists' observations of general cognitive activities of daily living (ADL) in depressed and healthy older adults (Goldstein, McCue, Rogers, & Nussbaum, 1992). The RBMT, as well as the TEA, have been found to be the best predictors of general functional impairment in multiple sclerosis (MS) patients compared to traditional cognitive tests (Higginson et al., 2000). The TEA was also successful in detecting cognitive aging effects in attentional processes in healthy old adults (Robertson et al., 1994). The CAMPROMPT was a significant predictor of the occupational performance (e.g., returning to work, withdrawal, or compromised performance) in MS patients (Honan, Brown, & Batchelor, 2015), and the BADS was significantly associated with everyday executive skills (Evans, Chua, McKenna, & Wilson, 1997) and general cognitive performance (Norris & Tate, 2000) in neurological patients and healthy individuals. Equally, the Trail Making

Table 5. Descriptive statistics for the VR-EAL, paper-and-pencil tests, and questionnaires

	<i>N</i>	Mean (SD)	Range
Gaming experience	41	6.12 (3.95)	2–13
VR experience	41	3.29 (1.29)	2–6
Total time VR-EAL (in minutes)	41	63.95 (7.88)	50–81
Total time VR session (in minutes)	41	73.95 (7.88)	60–91
Total Time Paper–Pencil Assessment (in minutes)	41	85.41 (3.97)	76–92
CAMPROMPT – total score (max = 36)	41	30.83 (3.49)	24–36
VR-EAL – PM total score (max = 48)	41	35.78 (4.73)	24–46
CAMPROMPT – event-based (max = 18)	41	16.39 (1.63)	12–18
VR-EAL – total event-based (max = 24)	41	18.15 (3.26)	8–24
CAMPROMPT – time-based (max = 18)	41	14.44 (2.66)	10–18
VR-EAL – time-based (max = 18)	41	11.63 (3.10)	6–18
RBMT – Immediate Recall (max = 21)	41	14.93 (2.24)	10–18
VR-EAL – Immediate Recognition (max = 20)	41	15.51 (1.98)	10–18
RBMT – Delayed Recall (max = 21)	41	15.98 (2.61)	11–21
VR-EAL – Delayed Recognition (max = 20)	41	17.17 (2.42)	12–20
TEA – Map Total Score (max = 80)	41	70.32 (6.87)	52–82
VR-EAL – Selective Visual Attention Accuracy (max = 32)	41	22.98 (3.84)	17–30
RSAT – Accuracy (max = 59)	41	47.51 (7.14)	27–58
VR-EAL – Selective Visual Attention Speed (max = 32)	41	23.61 (3.69)	18–30
RSAT – Speed (max = 80)	41	57.78 (9.39)	33–74
VR-EAL – Selective Visuospatial Attention Total (max = 20)	41	12.00 (2.42)	4–15
VR-EAL – Selective Visuospatial Attention Speed (max = 16)	41	11.90 (1.50)	8–14
VR-EAL – Selective Visuospatial Attention Accuracy (max = 16)	41	12.10 (1.18)	8–13
TEA – Elevator Counting with Distraction (max = 10)	41	9.05 (1.05)	7–10
VR-EAL – Selective Auditory Attention (max = 32)	41	29.56 (3.66)	20–32
BADS – Key Search (max = 16)	41	14.20 (1.47)	10–16
VR-EAL – Planning (max = 19)	41	14.90 (1.51)	11–17
CTT – 1 (max = 80)	41	49.37 (8.65)	32–68
VR-EAL – Cooking Task (max = 16)	41	9.68 (2.57)	2–13
CTT – 2 (max = 80)	41	55.20 (9.94)	27–70

BADS = Behavioral Assessment of Dysexecutive Syndrome; CAMPROMPT = Cambridge Prospective Memory Test; CTT = Color Trails Test; RBMT = Rivermead Behavioral Memory Test; TEA = Test of Everyday Attention; VR-EAL = Virtual Reality Everyday Assessment Lab.

Table 6. Bayesian correlations between users' experience and the sessions' durations

Correlational pairs	<i>r</i>	BF ₁₀	SP
Gaming experience – VR experience	0.84***	1.72e+10	~100%
VR experience – VR session duration	–0.60***	690.55	99%
Gaming experience – VR session duration	–0.55***	136.41	97%
Gaming experience – Paper-and-pencil session duration	–0.45***	12.17	94%
VR session duration – Paper-and-pencil session duration	0.53***	87.22	97%

The alternative hypothesis specifies that the correlation is positive. *BF₁₀ > 10; **BF₁₀ > 30; ***BF₁₀ > 100; *r* = Pearson's *r*; SP = Statistical Power at $\alpha < .05$.

Test B (i.e., comparable to CTT-2) was a significant predictor of the everyday executive skills of neurological (Burgess et al., 1998) and TBI patients (Chaytor, Schmitter-Edgecombe, & Burr, 2006). Lastly, the RSAT was found to be a key predictor of TBI patients' ability to return to professional or academic environments after rehabilitation (Ruff et al., 1993).

Our findings regarding the convergent validity of the VR-EAL tasks with the corresponding paper-and-pencil tasks that

have been established as predictors of real-world performance support the VR-EAL's ability to reflect performance outcomes in everyday life. However, the ecological validity of the VR-EAL would benefit from future work directly comparing the VR-EAL with true real-world functioning. For example, studies have shown that performance on real-world tasks (e.g., household chores) is significantly associated with self-ratings of instrumental activities of daily living (IADL) and independence questionnaires (Weakley, Weakley, &

Table 7. Bayesian correlations between the VR-EAL and the Paper-and-Pencil tests

Paper-and-Pencil scores	VR-EAL scores	r	BF ₁₀	SP
CAMPROMPT – Total	Total PM	0.82***	3.20e+9	~ 100%
CAMPROMPT – Event-based	Event-Based PM	0.73***	3.97e+3	~ 100%
CAMPROMPT – Time-based	Time-Based PM	0.67***	2.61e+2	~ 100%
RBMT – Immediate recall	Immediate Recognition	0.77***	7.34e+7	~ 100%
RBMT – Delayed recall	Delayed Recognition	0.82***	3.90e+9	~ 100%
TEA – Map total score	Selective Visual Attention Accuracy	0.48**	50.53	95%
TEA – Map total score	Selective Visual Attention Speed	0.46**	34.99	93%
RSAT – Accuracy	Selective Visual Attention Accuracy	0.43*	16.94	89%
RSAT – Accuracy	Selective Visuospatial Attention Total Score	0.61***	2101	99%
RSAT – Speed	Selective Visuospatial Attention Speed	0.49**	63.15	96%
RSAT – Accuracy	Selective Visuospatial Attention Accuracy	0.58***	778.50	99%
TEA – Elevator	Selective Auditory Attention	0.70***	8.91e+4	~100%
Counting with Distraction				
BADS – Key Search	Planning	0.80***	4.65e+8	~ 100%
CTT – 1	Planning	0.47**	41.74	94%
CTT – 2	Planning	0.51***	109.73	97%
CTT – 1	Cooking Task	0.70***	9.88e+4	~ 100%
CTT – 2	Cooking Task	0.80***	8.75e+8	~ 100%
BADS – Key Search	Cooking Task	0.62***	2.99e+3	99%

The alternative hypothesis specifies that the correlation is positive. *BF₁₀ > 10; **BF₁₀ > 30; ***BF₁₀ > 100; r = Pearson's r; SP = Statistical Power at $\alpha < .05$; BADS = Behavioral Assessment of the Dysexecutive Syndrome; CAMPROMPT = Cambridge Prospective Memory Test; CTT = Color Trails Test; PM = Prospective Memory; RBMT = Rivermead Behavioral Memory Test; RSAT = Ruff 2 and 7 Selective Attention Test; TEA = Test of Everyday Attention; VR-EAL = Virtual Reality Everyday Assessment Lab.

Schmitter-Edgecombe, 2019), which produce reliable and generalizable outcomes (Bottari, Dassa, Rainville, & Dutil, 2010; Bottari, Shun, Le Dorze, Gosselin, & Dawson, 2014). Thus, the predictive ability and/or veridicality of the VR-EAL could be further examined by investigating its relationship with real-world tasks and/or established IADL questionnaires in healthy older adults and/or clinical populations.

Nevertheless, considering that the verisimilitude approach may be more efficient than the veridicality approach in predicting everyday performance (Chaytor & Schmitter-Edgecombe, 2003; Spooner & Pachana, 2006), our findings suggest that VR-EAL's high verisimilitude is an advantage over other ecological valid tests. Previous studies examining the ecological validity of other VR neuropsychological tools have not considered users' perceptions of the task's verisimilitude (e.g., Canty et al., 2014; Jansari et al., 2014; Logie et al., 2011; Rand et al., 2009). Therefore, a further advantage of VR-EAL is that the participants rated it as more similar to the tasks that they perform in their daily life (i.e., more ecologically valid in terms of verisimilitude) than all tests in the paper-and-pencil neuropsychological battery and the group of well-established ecological valid tests with verisimilitude (i.e., CAMPROMPT test, RBMT-Story Recall, BADS-Key Search, TEA-Map, and TEA-Elevator Counting with Distraction). Furthermore, the VR-EAL tasks were individually compared to their corresponding paper-pencil test, where the results postulated that the VR-EAL tasks are significantly more ecologically valid in terms of verisimilitude than the equivalent paper-pencil tests. Also, as far as we are aware, our study is the first to compare the

pleasantness of the testing experience between immersive VR and paper-and-pencil tests. Here, the full version of the VR-EAL was also considered by the participants to be a more pleasant testing experience than the paper-and-pencil neuropsychological battery. Furthermore, the duration of the entire VR session (i.e., the induction and performance of VR-EAL) was considerably shorter than the administration time for the paper-and-pencil neuropsychological battery. Therefore, the VR-EAL emerges as substantially more enjoyable and ecologically valid testing experience with a significantly shorter administration time in comparison with the equivalent paper-and-pencil neuropsychological battery.

Age and education did not correlate with performance on the VR-EAL or the paper-and-pencil tests. While the paper-and-pencil scores were adjusted for age and education, the VR-EAL scores were not. Therefore, the VR-EAL may have the advantage that performance is not dependent on age or education. However, this needs to be further investigated in a larger and more diverse population, as the population of this study predominantly comprised younger adults aged 18–45 years with a relatively high level of education (i.e., 10–16 years).

Gaming experience strongly and positively associated with VR experience, indicating that gamers are also more experienced immersive VR users. Also, VR and gaming experience were both negatively correlated with the duration of the VR session, where more experienced gamers complete the assessment faster than non-gamers. Interestingly, however, the gaming experience was also correlated with the duration of the paper-and-pencil session, indicating that

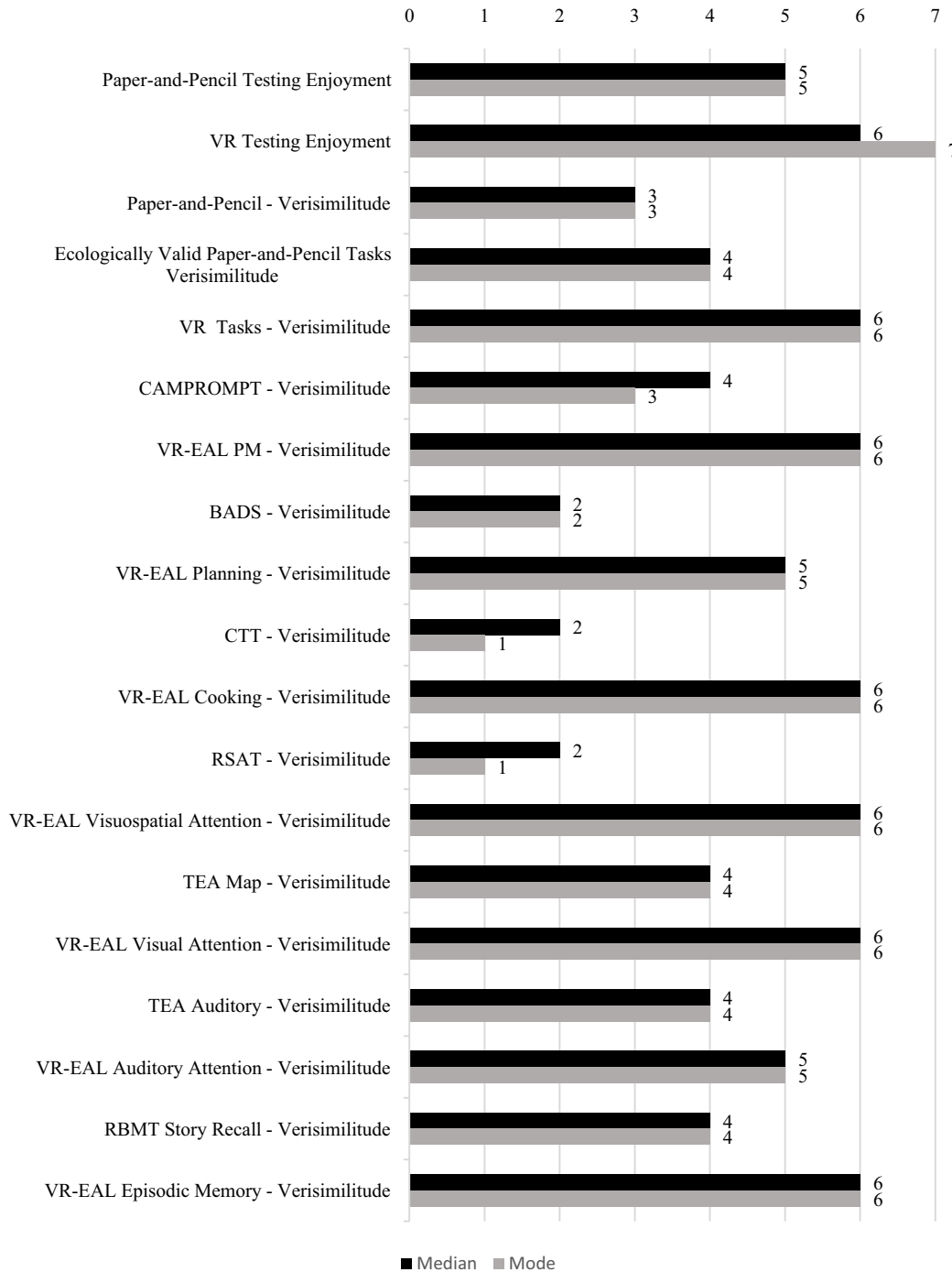


Fig. 3. Self-report verisimilitude and enjoyment of the VR-EAL and paper-and-pencil tests. BADS = Behavioral Assessment of the Dysexecutive Syndrome; CAMPROMPT = Cambridge Prospective Memory Test; CTT = Color Trails Test; PM = Prospective Memory; RBMT = Rivermead Behavioral Memory Test; RSAT = Ruff 2 and 7 Selective Attention Test; TEA = Test of Everyday Attention; VR = Virtual Reality; VR-EAL = Virtual Reality Everyday Assessment Lab.

gamers complete the paper-and-pencil assessment faster than non-gamers. Finally, the duration of the VR session was correlated significantly with that of the paper-and-pencil session, which also indicates that the speed of performing tasks affects the duration of both types of tasks (i.e., immersive VR and paper-and-pencil). Our findings are aligned with the relevant literature where gamers have been found to have enhanced

perceptual processing speed (Anguera et al., 2013; Dye, Green, & Bavelier, 2009; Kowal, Toth, Exton, & Campbell, 2018). However, in our sample, the gaming ability was not associated with the performance on the cognitive tests, indicating that gaming ability is not linked with an improved overall cognition, which is also in line with the relevant literature (Kowal et al., 2018).

Table 8. Comparison between administration time and participants' ratings of verisimilitude and enjoyment for the VR-EAL and paper-and-pencil tests

Paper-and-Pencil Test		VR-EAL	BF ₁₀	SP
Total Administration Time	>	VR-Session Time	1.224e+11 ^{***}	~ 100%
Testing Pleasantness	<	VR-Testing Pleasantness	188,842 ^{***}	~ 100%
Total Verisimilitude	<	VR-EAL Verisimilitude	4.898e +15 ^{***}	~ 100%
Ecologically Valid Tests/Tasks Verisimilitude	<	VR-EAL Verisimilitude	3.575e +13 ^{***}	~ 100%
CAMPROMPT Verisimilitude	<	PM Verisimilitude	1.179e +9 ^{***}	~ 100%
BADS Key Search Verisimilitude	<	Planning Verisimilitude	1.950e +13 ^{***}	~ 100%
CTT Verisimilitude	<	Cooking Task Verisimilitude	6.849e +21 ^{***}	~ 100%
RSAT Verisimilitude	<	Visuospatial Attention Verisimilitude	2.635e +13 ^{***}	~ 100%
TEA Map Verisimilitude	<	Visual Attention Verisimilitude	3.774e +12 ^{***}	~ 100%
TEA Elevator Counting with Distraction Verisimilitude	<	Auditory Attention Verisimilitude	4.36e +11 ^{***}	~ 100%
RBMT Story Recall Verisimilitude	<	Episodic Memory Verisimilitude	1.244e +7 ^{***}	~ 100%

*BF₁₀ > 10; **BF₁₀ > 30; ***BF₁₀ > 100; SP = Statistical Power at $\alpha < .05$; BADS = Behavioral Assessment of the Dysexecutive Syndrome; CAMPROMPT = Cambridge Prospective Memory Test; CTT = Color Trails Test; PM = Prospective Memory; RBMT = Rivermead Behavioral Memory Test; RSAT = Ruff 2 and 7 Selective Attention Test; TEA = Test of Everyday Attention; VR = Virtual Reality; VR-EAL = Virtual Reality Everyday Assessment Lab.

Another aim of the study was to provide immersive VR software for clinical and research use that has minimal VR-ISE since adverse symptomology associated with VR can significantly decrease participants' reaction times and overall cognitive performance (Nalivaiko et al., 2015; Nesbitt et al., 2017; Mittelstaedt et al., 2019). Albeit that the incidence of VR-ISE is more frequent in immersive VR, these symptoms are also highly frequent in non-immersive VR (Sharples et al., 2008). However, the examination and report of VR-ISE have not been considered in non-immersive VR studies of neuropsychological tools for clinical and research purposes (e.g., Canty et al., 2014; Jansari et al., 2014; Logie et al., 2011; Rand et al., 2009). Similarly, the examination of VR-ISE is under-reported or not examined in immersive VR studies of neuropsychological tools (Kourtesis et al., 2019a).

In contrast, the examination and report of VR-ISE were central in our endeavor to scrutinize the suitability of VR-EAL as a neuropsychological tool for research and clinical purposes. Our current findings replicate those of our previous work where VR-EAL did not induce VR-ISE in participants (Kourtesis et al., 2020). In this study, VR-EAL exceeded the parsimonious cut-offs for the VRNQ scores (total score, user experience, game mechanics, in-game assistance, and VR-ISE). The outcomes of VRNQ hence postulate that VR-EAL is a suitable VR software for implementation in research and clinical settings, without inducing VR-ISE. On all VR-ISE items, except fatigue, there was an absence of adverse symptoms. Participants reported only very mild feelings of fatigue albeit that this was an expected outcome since the duration of VR-EAL was around 60 min. However, fatigue was equally present during the paper-and-pencil session (80 min).

This study also has some limitations. The sample was moderately small ($N = 41$), though, every statistical analysis displayed a substantially robust statistical power (>90%). Moreover, as the current study is the first to provide validity for the VR-EAL, it was only administered to younger but not

older adults. Yet, the eventual aim is to use the VR-EAL to assess cognitive impairments in healthy aging and dementias (Anderson & Craik, 2017) or attention-deficit/hyperactivity disorder and autism (Karalunas et al., 2018). Future work should examine the performance and experiences of different clinical populations performing the VR-EAL to provide further evidence for the clinical utility of VR-EAL for assessing everyday cognitive functioning.

In summary, this study provides evidence supporting the validation of VR-EAL as an effective neuropsychological tool with enhanced ecological validity for the assessment of everyday cognitive functioning. In addition, the VR-EAL does not seem to induce VR-ISE (i.e., cybersickness). Therefore, our preliminary findings support the VR-EAL as an immersive VR assessment tool that has the potential to be implemented in both research and clinical settings in the future.

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CONFLICT OF INTEREST

The authors have nothing to disclose.

SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit <https://doi.org/10.1017/S1355617720000764>

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