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# Neurocognitive and Psychophysiological Analysis of Human Performance within Virtual Reality Environments

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**Abstract.** Monitoring the neurocognitive and psychophysiological activity of persons operating within a complex environment poses exacting measurement challenges. Three experiments are reported in this paper. In these experiments we made use of VRCPAT to assess persons' neurocognitive and psychophysiological responses to high-fidelity, immersive virtual environments. The first experiment provided continued support for the validity of the VRCPAT as a measure of learning and memory through the use of an increased sample size. In the second experiment we aimed at assessing whether an increase in stimulus complexity would result in a significant decrease in performance on attentional tasks. We also wanted to see whether an increase in stimulus intensity would result in a significant decrease in performance on attentional tasks. The third experiment looked at participants' psychophysiological responses in both low and high immersion virtual environments.

**Keywords.** Neuropsychological assessment, psychophysiology, ecological validity, virtual environment

## Introduction

While technological advances provide incredible potential for enhancing human-system capabilities to meet the demands of increasingly complex environments, the relentless pace of these advances, threatens to outstrip the human ability to adapt to new technologies. Understanding how this complexity affects a person's sensory, perceptual and cognitive performance of tasks presents opportunities for implementing novel systems that can exploit neurocogntive capabilities, rather than simply depending upon human adaptation, to improve and optimize human-system interactive performance. Monitoring the neurocognitive and psychophysiological activity of persons operating within a complex environment, however, poses exacting measurement challenges. Further, it is likely that neurocognitive functioning in operational versus tightly controlled laboratory environments will be significantly, if not fundamentally, different than in controlled laboratory settings.

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## 1. Virtual Environments

Virtual environments (VE) are now being developed and validated that focus on component cognitive processes including: attention processes [1], spatial abilities [2-3], learning and memory [4], and executive functions [5]. The ability of VEs to create dynamic, immersive, three-dimensional stimulus environments, in which all behavioral responding can be recorded, offers assessment and rehabilitation options that are not available using traditional assessment methods [6]. The potential for increased ecological validity of neurocognitive batteries that include assessment using VEs may aid differential diagnosis and treatment planning.

High-fidelity immersive virtual environments (VE) developed at the University of Southern California's (USC) Institute for Creative Technologies (ICT) are being leveraged to allow researchers to record psychophysiological measurement modalities during the performance of various highly-realistic tasks. Specifically, we aim to continue development of a comprehensive, standardized, norm-based virtual reality cognitive performance assessment test (VRCPAT) battery that recycles graphic assets developed at USC's ICT. The VRCPAT leverages VE assets to measure neurocognitive performance within ecologically valid environments. Neurocognitive components include attention, memory, executive functioning, spatial ability and a host of higher-level language and reasoning abilities.

The VRCPAT, a 3D virtual city environment, was designed to run on a Pentium 4 notebook computer with 1 GB RAM and a 128-MB DirectX 9 compatible graphics card. The primary aim of the current project was to use the already existing library (USC's ICT) of assets as the basis for creating a virtual reality (VR) application for the standardized assessment of neurocognitive performance within a contextually relevant VE.

The application uses the ICT's FlatWorld Simulation Control Architecture (FSCA). The FSCA enables a network-centric system of client displays driven by a single controller application. The controller application broadcasts user-triggered or scripted-event data to the display client. The real-time 3D scenes are presented using Numerical Design Limited's (NDL's) Gamebryo graphics engine. The content was edited and exported to the engine using Alias's Maya software.

Three-dimensional visual imagery is presented using the eMagin z800. Navigation through the scenario uses a common USB Logitech game pad device. We believe that the head-mounted display (HMD) approach provides the optimal level of immersion and interaction for this application at a cost that now rivals that of a high-quality flat-screen display. The VRCPAT software is a 3D VE programmed to simulate a city environment. During immersion in the VRCPAT, participants are seated at a desk and have a complete 360-degree view of the city environment.

## 2. Three Experiments using the Virtual Reality Cognitive Performance Assessment Test

Three experiments are reported in this paper. In these experiments we made use of VRCPAT to assess persons' neurocognitive and psychophysiological responses to high-fidelity, immersive virtual environments. The first experiment provided continued support for the validity of the VRCPAT as a measure of learning and memory—herein we provide results from an increased sample size. Participants took part in an evaluation of the construct validity of the VRCPAT. In addition to completing the

VRCPAT Memory Module, they completed an in-person neuropsychological assessment. Participants included a sample of 67 healthy adults. In the second experiment we aimed at assessing whether an increase in stimulus complexity would result in a significant decrease in performance on attentional tasks. We also wanted to see whether an increase in stimulus intensity would result in a significant decrease in performance on attentional tasks. The study sample included 12 healthy adults. The third experiment looked at 14 participants' psychophysiological responses in both low and high immersion virtual environments. For all studies, participants were comparable in age, education, ethnicity, sex, and self-reported symptoms of depression. Strict exclusion criteria were enforced for all three experiments so as to minimize the possible confounding effects of comorbid factors known to adversely impact cognition, including psychiatric (e.g., mental retardation, psychotic disorders, diagnosed learning disabilities, Attention-Deficit/Hyperactivity Disorder, and Bipolar Disorders, as well as substance-related disorders within two years of evaluation) and neurologic (e.g., seizure disorders, closed head injuries with loss of consciousness greater than 15 minutes, and neoplastic diseases) conditions.

### *2.1 Experiment 1: Further Validation of the Virtual Reality Cognitive Performance Assessment Test*

To build upon earlier validation [4] of the VRCPAT as a measure of learning and memory, recall indices from the VRCPAT and traditional neuropsychological tests were correlated in a much larger sample (N=67).

The VRCPAT Memory Module is a 15-minute measure, in which participants "traveled" to five zones in a virtual city and attempted to identify 10 targets (2 targets at each of the 5 zones). At each of the five zones, the participants were exposed to both targets (i.e., items from a previously learned 10-item list) and foils (i.e., items that were similar to or different from—but not identical to—the targets). A psychometrist scored the participants' performance during the acquisition phase (i.e. Learning Domain), which made up the VRCPAT's Learning score. The VRCPAT memory score resulted from the retrieval phase (i.e. Memory Domain). The psychometrist recorded the total delayed recall from within the five zones. Again, each of the five zones had two targets.

The following traditionally used paper and pencil neuropsychological measures were used as convergent validity measures, because each is considered to have an important memory component and has been used clinically to estimate memory abilities: To assess verbal learning and memory we used the Hopkins Verbal Learning Test – Revised (HVLT); to assess nonverbal learning and memory we used the Brief Visuospatial Memory Test – Revised (BVMT).

Discriminant validity measures that were drawn from the corpus of traditionally used paper and pencil neuropsychological measures included: to assess Attention we used Digit Span (Forward and Backward) from the Wechsler Adult Intelligence Scale –Third edition; to assess processing speed we used Digit Symbol Coding from the Wechsler Adult Intelligence Scale –Third edition; and Trail Making Test Part A; to assess verbal fluency we used Controlled Oral Word Association Test (FAS and Animals); and to assess executive functioning we used Trail Making Test Part B and the Stroop Color and Word Test.

Indices were developed from linear composites derived from z-score transformations. Specifically, Pearson correlation analyses were used to compare recall from the VRCPAT with linear composites derived from traditional neuropsychological measures. The results indicated that the VRCPAT correlated significantly with the traditional neuropsychological Learning Composite (HVLT Trials 1-3; and BVMT Trials 1-3; $r = 0.72$, $p < 0.001$), with 52% variance shared between the two indices. The VRCPAT also correlated significantly with the traditional neuropsychological Memory Composite (HVLT Total Recall after a Delay; and BVMT Total Recall after a Delay; $r = 0.68$, $p < 0.001$), with 46% variance shared between the two indices. As expected, there were no significant correlations between VRCPAT measures and the following neuropsychology test composites: Executive Functions; Attention; or Processing Speed. Hence, each of the discriminant validity significance tests were as predicted, that is, did not correlate with theoretically unrelated abilities.

### 2.2 *Experiment 2: Attentional Assessment using the Virtual Reality Cognitive Performance Assessment Test*

In Experiment 2, participants' attentional processing was assessed using manipulation of stimulus "intensity" and stimulus "complexity" while they took part in a "HUMVEE Attention Task" scenario. The task involved the presentation of a four_digit number that was superimposed on the virtual windshield (of the Humvee) as the participants drove the Humvee. Stimulus "complexity" was relative to the presentation of stimuli. For "simple" presentations, the four_digit number always appeared in a fixed central location on the "windshield." For the "complex" presentations, the numbers appeared randomly throughout the "windshield" rather than in one fixed central location. Stimulus "intensity" was modulated by placing the user in "safe" (low intensity) and "ambush" (high intensity) settings: start section; palm ambush; safe zone; city ambush; safe zone; and bridge ambush. Herein we report on scenario differences: 1) comparison of attentional performance in "simple" stimulus presentations versus "complex" stimulus presentations; and 2) comparison of attentional performance in "low intensity" versus "high intensity" stimulus presentations.

To examine scenario differences, one-way ANOVAs were performed, comparing attentional performance in "simple" stimulus presentations (Mean = 43.63; SD = 8.91) versus "complex" stimulus presentations (Mean = 34.63; SD = 6.86). The results indicated that the increase in stimulus complexity caused a significant decrease in performance on attentional tasks ($F = 5.12$; $p = 0.04$). To examine scenario differences, we compared attentional performance in "low intensity" (Mean = 40.01; SD = 4.06) versus "high intensity" (Mean = 9.25; SD = 3.70) presentations. The results indicated that the increase in stimulus intensity caused a significant decrease in performance on attentional tasks ($t = 9.83$; $p = 0.01$).

### 2.3 *Experiment 3: Psychophysiological Assessment of Immersion using the Virtual Reality Cognitive Performance Assessment Test*

In the third experiment the impact of highly immersive virtual reality on participants' psychophysiological responses was compared with responses to a less immersive experience of watching the scenario on a laptop screen. The "high immersion" condition utilized a head-mounted display, headphones, and a tactile transducer. In the "low immersion" condition, participants wore headphones and watched the scene on a laptop computer screen. The stimuli were a series of military scenes that occurred while participants drove a Humvee, intermittently probed with acoustic startles. Dependent measures included two psychophysiological measures and responses on two self-report questionnaires (Tellegen Absorption Scale and Immersive Tendencies Questionnaire).

To examine differences in levels of immersion, a one-way ANOVAs was performed, comparing median startle eyeblink amplitudes in "high immersion" (Mean = 0.29; SD = 0.09) versus "low immersion" scenarios (Mean = 0.18; SD = 0.03). The results indicated that the increase in immersion caused a significant increase in median startle eyeblink amplitudes ($F = 19.17$; $p < 0.001$). Participants' cardiac responses showed a similar trend as the median beats per minute (BPM) in the "high immersion" condition (Mean = 86.71; SD = 47.75) were higher than median BPM in the "low immersion" condition (Mean = 61.21; SD = 11.29). This trend approached significance ($F = 7.918$; $p < 0.005$), corroborating the EMG finding that "high immersion" scenarios evoke a stronger physiological reaction than "low immersion" scenarios.

## 3. Discussion

Three experiments are reported in this paper. In these experiments we made use of VRCPAT to assess persons' neurocognitive and psychophysiological responses to high-fidelity, immersive virtual environments. The first experiment provided continued support for the validity of the VRCPAT as a measure of learning and memory. In the second experiment we found that an increase in stimulus "complexity" resulted in a significant decrease in performance on attentional tasks. We also found that an increase in stimulus "intensity" resulted in a significant decrease in performance on attentional tasks. The third experiment looked at participants' psychophysiological responses in both "low" and "high" immersion presentations of the virtual environments.

In the first experiment participants took part in an ongoing evaluation of the construct validity of the VRCPAT. The results of this study indicate that: 1) VRCPAT memory measures correlated significantly with scores from the memory measures drawn from the traditional neuropsychological test battery; and 2) VRCPAT memory scores did not correlate with non-memory measures drawn from the traditional neuropsychological test battery. Additionally, no negative side effects were associated with use of the VRCPAT. The establishment that the VRCPAT's memory measures correlated significantly with scores from the memory measures drawn from the traditional neuropsychological test battery but not with non-memory measures removed the possibility that results reflected correlates of the non-target construct (e.g. processing speed; executive function).

Attention processes are the gateway to information acquisition and serve as a necessary foundation for higher-level neurocognitive functioning. In the second experiment we aimed at assessing whether an increase in stimulus "complexity" would result in a significant decrease in performance on attentional tasks. We also wanted to see whether an increase in stimulus "intensity" would result in a significant decrease in performance on attentional tasks. The results indicated that the increase in stimulus "complexity" did in fact cause a significant decrease in performance on attentional tasks. Likewise, results from assessment of attentional performance in "low intensity" versus "high intensity" presentations. The results indicated that the increase in stimulus intensity caused a significant decrease in performance on attentional tasks. Hence, findings suggest that the increase in stimulus complexity and stimulus intensity within a virtual environment can manipulate performance on attentional tasks.

The third experiment looked at participants' psychophysiological responses in both "low immersion" and "high immersion" virtual environments. Our examination of differences in levels of immersion revealed that the increase in immersion caused a significant increase in median startle eyeblink amplitudes. Participants' cardiac responses showed a similar trend as the median beats per minute (BPM) in the "high immersion" condition were greater than median BPM in the "low immersion" condition. This trend approached significance, corroborating the EMG finding that "high immersion" scenarios evoke a stronger physiological reaction than "low immersion" scenarios. Interestingly, the standard deviation was also much higher in the "high immersion" condition, suggesting that highly immersed participants responded strongly to events in the scenario rather than simply experiencing a generalized state of hyperarousal. These findings suggest that highly immersive virtual reality experiences evoke greater psychophysiological responses than less immersion experiences, suggesting a stronger impact on the participant.

Our goal was to conduct three experiments that assess the utility of the VRCPAT as a measure of neurocognitive functioning. We believe that this goal was met. We recognize, however, that the current findings are only initial steps in the development of this tool. Many more steps are necessary to continue the process of test development and to fully establish the VRCPAT as a measure that contributes to existing assessment procedures for the assessment of neurocognitive and psychophysiological functioning.

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