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The DETECT^{TM} System: portable, reduced-length neuropsychological testing for mild traumatic brain injury via a novel immersive environment

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Undiagnosed mild traumatic brain injury (mTBI) often leads to poor patient management and significant morbidity. The lack of an efficient screening tool is especially apparent in the athletic setting, where repetitive injuries can lead to prolonged disability. We have developed the Display Enhanced Testing for Concussions and mTBI system (DETECT^{TM}), in order to create a portable immersive environment that could eliminate visual and audio distractions. Neuropsychological tests sensitive to mTBI were modified for use with the system and allow rapid neurological assessment independent of the environment or trained personnel. We evaluated the immersive qualities of the DETECT^{TM} system in 42 uninjured controls. The system was successful in blocking out external audiovisual stimuli. The neuropsychological test results obtained in a stimulus rich environment were equivalent to those obtained in a controlled quiet environment. The immersive environment, portability, and brevity of the DETECT^{TM} system allow for real-time cognitive testing in situations previously deemed impractical or unavailable for mTBI patients.

1. Introduction

In the United States, over 750 000 mild traumatic brain injuries (mTBI) occur every year [1]. mTBI can result in long-term disability or death from secondary complications when not properly diagnosed [2–4]. However, the diagnosis of mTBI is difficult even in the best setting, because the signs and symptoms can be very subtle. Often, mTBI is overshadowed by other injuries or by the events surrounding the incident. Undiagnosed mTBI leads to poor clinical management and can often lead to psychosocial problems and secondary complications, including depression [5–14]. The lack of a rapid screening tool is especially apparent in athletic settings, where repetitive injuries in children and young adults can lead to prolonged disabilities and death [11,13].

The conventional method for evaluating mTBI is neuropsychological testing. However, this requires a quiet room empty of distractions, and the presence of trained personnel to administer, score and interpret the results. In addition, these tests may take several hours to perform. In many situations, such as sideline assessment of concussion during sporting events, or in an emergency room setting, these requirements make standard neuropsychological testing impractical. The challenge was to develop a method by which neuropsychological testing could be performed rapidly (15 minutes or less), without an expert examiner, and in an otherwise distracting environment.

These challenges led us to develop a novel solution: the Display Enhanced Testing for Concussions and mTBI system (DETECT^{TM}). The system creates an immersive environment free from visual and auditory distractions (the quiet room) for neuropsychological testing (the ideal testing methodology) in the field (portability and independent of an examiner) for applications such as sideline assessment of concussion in sports, emergency department evaluations, and military applications. The device combines this immersive environment with neuropsychological tests that

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were computerized and shortened by reducing the number of trials used in the paper and pencil version. Further brevity was achieved by requirement for rapid user input and automated progression of the test questions. Audio instructions are fed into the noise-reducing earphones and responses are tracked through a data acquisition log. The neuropsychological tests are autoscored to provide immediate feedback.

The objectives of the study were (1) to design a portable system that creates an immersive visual and auditory environment; (2) to adapt existing neuropsychological tests known to be sensitive to mTBI so that they could be integrated into a simple software program; and (3) to test the immersiveness of DETECT™ in normal subjects.

2. Methods

2.1. Objective 1: Designing the DETECT™ Prototype

The DETECT™ apparatus incorporated off-the-shelf hardware and custom software adapted from neuropsychological tests previously validated for mTBI [15–19] (figure 1).

The head-mounted display used to present the software consisted of a Sony Glasstron LDI-100BE personal LCD monitor (Toyko, Japan). A custom-made cardstock visor was positioned around the Glasstron frame to block out external light. Bose® Aviation Headset X active noise reduction (ANR) headphones (Bose Corporation; Framingham, MA, USA) were used to play the audio instructions while blocking out external noise. Two Jelly Bean® switches (AbleNet, Inc., Minneapolis, MN) were connected to an X-keys USB Switch Interface and programmed to respond as a 'yes' or 'no' button. The 'yes' button was held in the user's dominant hand and the 'no' button was held in the user's nondominant hand. This immersive environment is contained in a single headset, rendering the device convenient and portable. A Dell Latitude C840 notebook computer (Austin, TX) with a Mobile Pentium® processor (2.2 GHz, 512 MB RAM, 40 GB hard drive) and a 64 MB DDR video card, Windows® XP Professional version 2002 (SP1) were used to run the software executable.

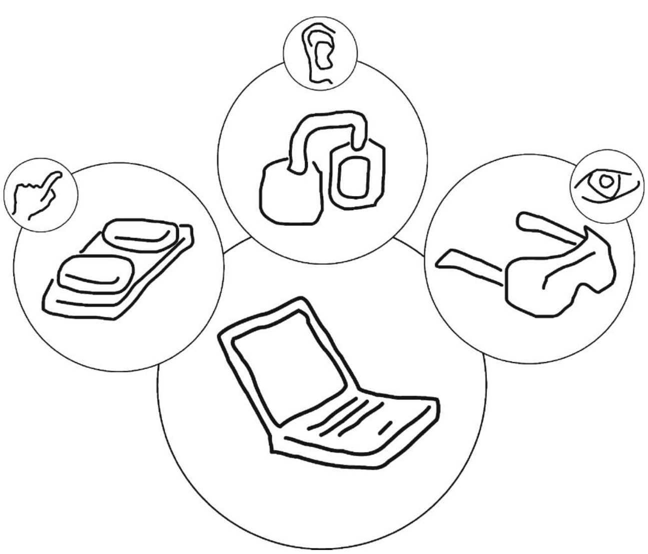

Figure 1. Hardware components of DETECT™.

2.2. Objective 2: Neuropsychological test development

Three standard neuropsychological tests that tapped cognitive processes and executive functions known to be especially sensitive to mTBI were abstracted, modified, and computerized for display on a virtual reality screen: (1) Simple & Complex Choice Reaction Time test [15], (2) Selective Reminding Memory Test [16,17], and (3) N-back Working Memory Test [18,19]. Each of the tests was reduced in length by incorporating fewer trials than used in the paper and pencil versions, to shorten the testing period. The tests run automatically and require rapid user input. Failure to input the correct answer in the appropriate time frame results in a miss-score (incorrect answer). This increases the challenge for the user and targets one of the more affected cognitive functions post mTBI, reaction time. Moreover, in the computerized version we have streamlined the instructions and reduced repetition. Each of the three tests takes no more than five minutes to complete, for a maximum total administration time of approximately 15 minutes.

2.2.1. Simple & Complex Choice Reaction Time. Three subtests made up the Simple & Complex Reaction Time test; each required the participant to respond to a stimulus by pressing a button as quickly as possible. A stimulus was displayed one at a time for 3 s or until the participant responded, at which time the next stimulus was displayed. Each subtest consisted of 30 stimuli that were black or coloured shapes, depending on the condition, drawn on a cream coloured background (figure 2). All stimuli were randomly selected prior to the onset of the condition. For each test, the mean reaction time in milliseconds was recorded.

The first subtest was a Simple Reaction Time test. The participant was asked to press the 'yes' button as quickly as possible in response to one of four black geometric shapes (target shape = a circle, square, triangle or diamond). In 30 trials, there was a 25% probability of the target shape being displayed.

The second subtest was an Easy Multiple Choice Reaction Time test where one of four black geometric shapes was chosen as the target. The participant was asked to press the 'yes' button to respond to a target and the 'no' button to respond to a nontarget. There was a 25% probability that the target would be displayed.

The third subtest was Complex Multiple Choice Reaction Time. The stimuli had three characteristics: shape, colour, and line orientation within the shape. The shape could be a circle, square, triangle or diamond. The colour could be blue, red, green or purple. The line orientation within the shape could be horizontal, vertical, forward slant (/), or backward slant (\). The target stimuli consisted of three specific characteristics, for example a blue circle with horizontal lines. Nontargets were all stimuli not containing all three of those characteristics. There was a 25% probability that a stimulus would be a target and a 50% probability that a stimulus would be a nontarget with only one or two of the target's characteristic states.

2.2.2. Selective Reminding Memory Test. Participants were asked to remember 12 target words displayed on the screen. The words were displayed in black text on a cream coloured background (figure 3). Each word was displayed on the screen one at a time for 3 s. Participants were then shown 24 words, 12 of which were the original target words and 12 were new distracter words. The participants were asked to press the 'yes' button with their dominant hand if the word displayed was one of the target words, and to press the 'no' button with their non-dominant hand if the word was a nontarget word. The words were displayed one at a time for 3 s or until the participant responded. The order in which the words appeared was random.

After each trial of 24 words, participants were shown the initial target words they did not correctly recognize. These words were displayed one at a time for 3 s. If the participants recognized all the target words, they were asked to complete another trial of 24 words containing 12 new distracters. The participants continued until they recognized all the stimulus words on two consecutive trials or until they completed a total of four trials. At the end of the entire DETECT^{TM} test, the participants completed one last trial to test their delayed recognition memory.

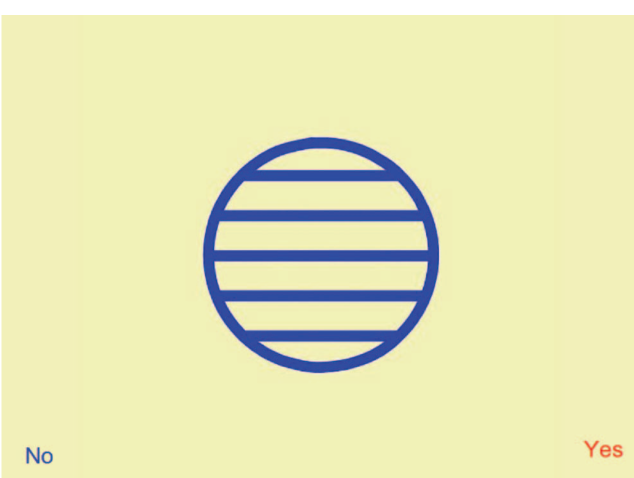

Figure 2. Complex Choice Reaction Time stimulus.

The words were selected from the Battig and Montague category norms [20]. For each target word on a Selective Reminding trial there was a distracter word in the same category. For example, if 'dog' was a target word, then 'cat' might be distracter word in the first recognition memory trial, 'bear' in the second trial, etc. Phonemically similar words, such as 'bear' and 'pear,' were also used.

2.2.3. N-back Working Memory Test. Participants were asked to respond either positively or negatively to a flashing white square on a 3 × 3 black grid (figure 4). The centre of the grid displayed a white X. The white square appeared at one of eight positions around this X. It was displayed for 100 ms, resulting in a flash once every 3 s. The positions of the squares were randomized prior to the beginning of the test. There were three levels of N-back tests: 0-back, 1-back, and 2-back. Participants completed each test twice.

Prior to completing the first test at each level, participants practised the tests and received visual feedback of

Figure 3. Selective Reminding Memory Test stimulus.

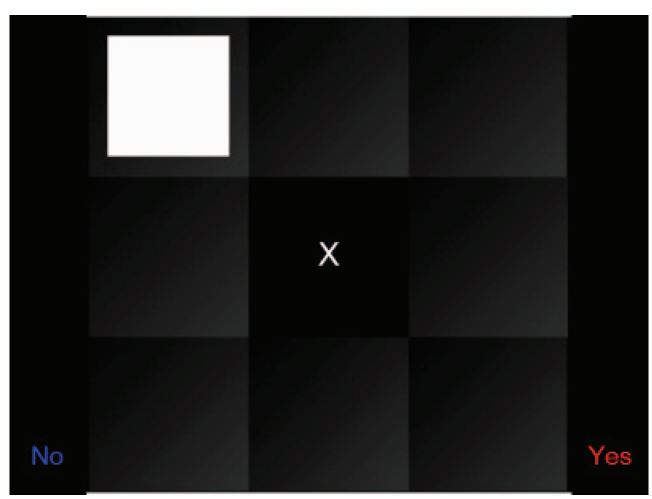

Figure 4. N-back Working Memory Test screen.

their responses; a 'check' appeared if the participant responded correctly, and an 'X' appeared if the participant responded incorrectly.

In the 0-back test, the participants were asked to press the 'yes' button with their dominant hand if the flashing square appeared in a particular position on the screen (i.e. top left corner of the screen). If it flashed in another position, the participants were asked to press the 'no' button with their non-dominant hand. In the 1-back test, the participants were asked to respond positively if the square flashed in the same position it did one flash earlier and negatively if it flashed in a new position. In the 2-back test, they were asked to respond positively if the square flashed in the same position it did two flashes earlier and negatively if it did not. Each test consisted of 16 flashes, of which about 33% required positive responses.

2.3. Objective 3: Testing the Immersiveness of DETECT^{TM} in normal subjects

2.3.1. Participants. The exclusion criteria (in part based on the display manufacturer's device warnings) were a history of head injury in the past six months, epilepsy, high blood pressure, cardiac disease, or visual impairment. The final sample included 42 uninjured Georgia Institute of Technology undergraduate students who volunteered for the study in exchange for extra class credit. All participants were 18 years of age or older. Of the participants 41 were right-handed and one was left-handed. All procedures were approved by the Georgia Institute of Technology Institutional Review Board.

2.3.2. Testing environment. The study was held in a laboratory (Institute of Paper Science and Technology Engineering Center) at the Georgia Institute of Technology. The DETECT^{TM} prototype was set up at a desk. Two speakers were set far apart behind the participant, pointing toward nearby walls to create an indirect and ambient sound field during the noisy environment test. The researcher started each test and played the audio sounds as needed, but did not interact with the participant while the tests were running. The researcher sat at a different desk in the room. The participants' responses were recorded and saved by the software.

2.3.3. Testing procedure. To simulate a noisy environment, an audio file containing a five-minute loop of layered, distracting noises was continuously repeated on the pair of speakers set up in the lab at an average volume of 75 dB. Participants completed the DETECT^{TM} test twice, once in the lab with simulated noise and once in the lab without additional noise, using two different full version tests (version A and version B). This counterbalanced design producing four participant groups was implemented both to limit the effects of learning from repeated exposures of the same version and to test the effect of a noisy environment on the results. Specifically, participants were randomized to a noisy or quiet initial environment and then those groups were randomized to take either test version A first followed by version B or test version B first followed by version A. To establish the equivalency of the different arms of the study, mean response time and overall score were compared for differences within each testing environment. A two-sample t-test was employed to make the comparison.

The input buttons were set up such that the participant pressed the 'yes' button with their dominant hand and the 'no' button with their non-dominant hand. The researcher described the hardware components. The researcher showed the participant how to adjust and wear the head mounted display and headphones to fit comfortably. A visor cover was placed over the display to block out peripheral vision. The usability study required approximately 45 minutes to complete.

The software recorded the participants' responses and reaction times to all the tests. After completing the DETECT^{TM} test twice, the participants were given a questionnaire to assess the effectiveness and comfort of the hardware components. They were asked to select their agreement level (Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree) to the following statements:

- I found the visual display comfortable to wear.
- I thought the visual display blocked out all visual distractions.
- I could easily see the visual display with both eyes.
- I found the earphones comfortable to wear.
- I thought the earphones blocked out all the outside noise.
- I could hear the auditory instructions clearly.
- I understood the auditory instructions.
- I thought the input device (yes and no buttons) was easy to use.
- I felt I could concentrate while taking the tests.
- I felt nervous while taking the tests.

2.3.4. Statistical methods. Performance on each of the three tests was summarized by determining the number of correct responses and dividing these by the total number of questions. Additionally, the DETECT^{TM} system reported the response time, in milliseconds, for the subject to respond to the stimuli; these data were summarized by calculating the mean response time for each of the three DETECT^{TM} tests.

The mean response time and overall score (percent correct) were used to evaluate the effect that the noisy or distracting environments had on participant performance. A two-sample t-test was used to compare the mean overall score and mean response times for each of the three

DETECT™ tests between subjects in the noisy environment and those in the quiet environment. With each participant taking the exam twice due to the crossover design of this study, between-group differences were calculated only for groups in a corresponding series (i.e. first test in noisy environment was compared to first test in quiet environment, etc). To evaluate potential learning effects, within-group differences were calculated using a two-sample t-test of the change in overall score and mean response time from test 1 to test 2.

Spearman correlations were calculated between the participant's scaled responses on the post-test questionnaire and their individual test performance, stratified by the environment (noisy versus quiet) and test order. The Spearman correlation was employed because the scaled responses did not meet the necessary assumptions regarding distribution.

3. Results

Performance did not differ systematically due to the testing environment (table 1). Subjects taking the test in the noisy environment first had a mean N-back, Selective Reminding, and Simple and Complex scores of 81.8% (95% CI = 76.1%, 87.6%), 86.2% (95% CI = 77.7%, 94.8%), and 94.7% (95% CI = 90.7%, 98.7%), respectively. Subjects taking the tests in the quiet environment first had comparable mean N-back, Selective Reminding, and Simple and Complex scores of 80.6% (95% CI = 74.6%, 86.7%; $p = 0.77$), 89.8% (95% CI = 81.7%, 979%), and 95.2% (95% CI = 92.0%, 98.4%), respectively (figure 5). Response times followed a similar pattern suggesting that the two different testing environments did not influence performance (figure 6).

Table 1. Performance using the DETECT™ system from the comparison between the noisy and quiet environments as a function of order of test environment.

	First exposure to DETECT			Second exposure to DETECT		
Test name	Noisy	Quiet	*p*-value	Noisy	Quiet	*p*-value
N-Back						
Average score (% correct) (95% CI)	81.8 (76.1, 87.6)	80.6 (74.6, 86.7)	0.77	86.3 (81.9, 90.6)	84.7 (78.2, 91.2)	0.68
Average response time (ms) (95% CI)	1.13 (0.97, 1.28)	1.21 (0.97, 1.44)	0.54	1.013 (0.876, 1.15)	1.003 (0.802, 1.204)	0.93
Simple & Complex						
Average score (% correct) (95% CI)	94.7 (90.7, 98.7)	95.2 (92.0, 98.4)	0.83	97.0 (93.9, 100)	98.7 (98.1, 99.3)	0.28
Average response time (ms) (95% CI)	1.24 (1.09, 1.38)	1.17 (1.00, 1.35)	0.55	1.12 (1.00, 1.23)	1.15 (1.07, 1.22)	0.66
Selective Reminding						
Average score (% correct) (95% CI)	86.2 (77.7, 94.8)	89.8 (81.7, 97.9)	0.53	91.8 (81.1, 100)	97.9 (97.1, 98.8)	0.25
Average response time (ms) (95% CI)	0.99 (0.84, 1.14)	0.95 (0.75, 1.15)	0.73	0.91 (0.66, 1.16)	0.77 (0.72, 0.82)	0.27
Trial 5 average score	84.4 (71.7, 97.0)	94.2 (90.9, 97.6)	0.13	90.6 (79.9, 100)	98.0 (96.5, 99.6)	0.16

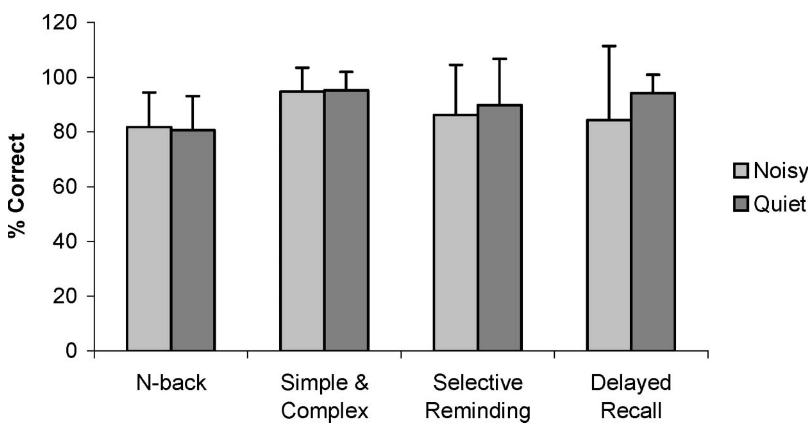

Figure 5. Comparison of test performance (% correct) using the DETECT™ system in a noisy and quiet environment.

The within-group analysis highlighted differences in learning patterns. Subjects taking the N-back test in the noisy environment first, followed by the quiet environment, experienced no significant change in their test performance (table 2). Subjects taking the N-back in the quiet environment first, followed by the noisy environment, showed a 4.8% (95% CI = 0.99%, 8.6%; $p = 0.002$) mean score improvement. Additionally, this group also reduced their response times by an average of 0.182 seconds (95% CI = 0.308, 0.056; $p = 0.007$) (table 3). However, learning differences on the Selective Reminding test followed the opposite pattern. Subjects taking the Selective Reminding test in the noisy environment first experienced an average score increase of 10.4% (95% CI = 1.72%, 19.2%; $p = 0.021$), and reduced their response times by an average of 0.208 seconds (95% CI = 0.063, 0.355; $p = 0.007$) when taking the test subsequently in the quiet environment. The within-group analysis for the Simple and Complex test revealed no significant change by response time, and only a small change by overall score among subjects taking the exam in the quiet environment first then proceeding to the noisy environment.

No statistically significant differences were observed between test versions A and B (table 4). However, examining only the cohort given the test in the noisy environment first there appeared to be a trend toward a difference in version A and B for the N-back test when taken in the quiet environment. In contrast, the data from the cohort given test in the quiet environment first trended toward subjects performing better on the A version of the N-back test in the quiet environment. In the noisy environment, among the cohort randomized to take the exam in the quiet environment first, the results for version B were better than those taking version A.

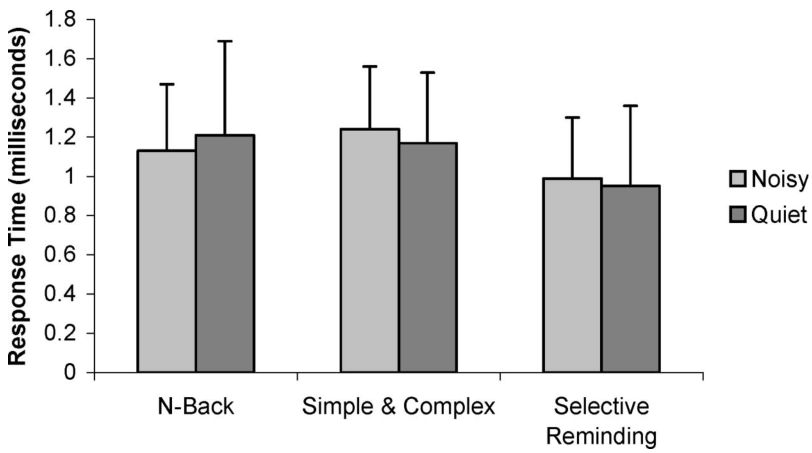

Figure 6. Comparison of response times (ms) when using the DETECT™ system in a noisy and quiet environment.

Table 2. The effects of learning on test scores (% correct) with the DETECT™ system.

	Noisy environment followed by quiet		Quiet environment followed by noisy	
Test name	Mean difference (95% CI)	*p*-value	Mean difference (95% CI)	*p*-value
N-back	2.9 (−2.5, 8.3)	0.12	4.8 (0.99, 8.6)	0.016
Simple & Complex	4.02 (0.076, 7.97)	0.046	1.48 (−0.393, 3.36)	0.12
Selective Reminding	10.4 (1.72, 19.2)	0.02	1.73 (−2.73, 6.18)	0.43
Selective Reminding Trial 5	13.8 (0.66, 26.8)	0.04	−1.78 (−11.6, 8.0)	0.71

Table 3. The effects of learning on reaction time with the DETECT™ system.

	Noisy environment follow by quiet		Quiet environment follow by noisy	
Test name	Mean difference (95% CI)	*p*-value	Mean difference (95% CI)	*p*-value
N-back Time	−0.122 (−0.279, 0.035)	0.28	−0.182 (−0.308, −0.056)	0.007
Simple & Complex Time	−0.092 (−0.228, 0.044)	0.175	−0.056 (−0.183, 0.071)	0.37
Selective Reminding Time	−0.208 (−0.355, −0.063)	0.007	−0.042 (−0.151, 0.067)	0.43

Table 4. Comparison of test performance on the two versions of the DETECT^{TM} test (Version A and Version B) stratified by order of environmental exposure. Subjects in Group 1 were first exposed to the noisy test-taking environment while subjects in Group 2 were first exposed to the quiet test-taking environment. When subjects crossed environments there was a concurrent crossing of test version. For example, subjects taking Test A were given Test B in the new environment.

	Noisy environment first			Quiet environment second		
	Version A Mean (SD)	Version B Mean (SD)	*p*-value†	Version A Mean (SD)	Version B Mean (SD)	*p*-value†
N-Back Test						
Response time	1.12 (0.34)	1.13 (0.36)	0.94	1.15 (0.55)	0.84 (0.20)	0.09‡
Overall score	83% (14%)	81% (12%)	0.80	79% (19%)	90% (4%)	0.11‡
Selective Reminding						
Response time	0.93 (0.23)	1.04 (0.37)	0.41	0.80 (0.10)	0.74 (0.09)	0.19
Overall score	90% (9%)	83% (23%)	0.45	98% (2%)	98% (0.8%)	0.74‡
Simple & Complex						
Response time	1.17 (0.33)	1.30 (0.31)	0.36	1.18 (0.21)	1.10 (0.08)	0.25‡
Overall score	95% (8%)	94% (10%)	0.83	98% (2%)	99% (1%)	0.32

† Calculated using the pooled two-sample t-test unless otherwise indicated.
‡ Calculated using a Satterthwaite two-sample t-test.

	Noisy environment second			Quiet environment first		
	Version A Mean (SD)	Version B Mean (SD)	*p*-value†	Version A Mean (SD)	Version B Mean (SD)	*p*-value†
N-Back Test						
Response time	1.14 (0.34)	0.90 (0.18)	0.07	1.02 (0.26)	1.41 (0.60)	0.10‡
Overall score	82% (12%)	90% (2%)	0.11‡	84% (9%)	77% (15%)	0.19
Selective Reminding						
Response time	1.06 (0.7)	0.77 (0.12)	0.28‡	0.81 (0.12)	1.10 (0.56)	0.16‡
Overall score	86% (32%)	97% (1%)	0.36‡	95% (3%)	84% (24%)	0.20‡
Simple & Complex						
Response time	1.22 (0.29)	1.03 (0.16)	0.10	1.17 (0.42)	1.18 (0.29)	0.93
Overall score	98% (5%)	96% (7%)	0.59	93% (8%)	98% (3%)	0.15‡

† Calculated using the pooled two-sample t-test unless otherwise indicated.
‡ Calculated using a Satterthwaite two-sample t-test.

Subjects taking version B in the noisy environment had a mean score 8% ($p = 0.11$) higher and were 0.24 seconds ($p = 0.07$) faster than those taking version A in the same environment.

Overall, participants' responses to the post-task questions related to the DETECT^{TM} experience did not appear to correlate with either overall performance or response time (table 5). Although statistically significant ($p \leq 0.05$) correlations were observed between response time and the level of outside noise blocked during the Simple and Complex test in the noisy environment first cohort, and response time and nervousness for the Simple and Complex test in the quiet environment second cohort, these correlations appear to result from type II error, as correlations were not consistently observed between similar environment and test order. However, participants' understanding of the auditory instructions correlated moderately with overall N-back performance, but only in the quiet environment. A moderate correlation between understanding auditory instructions and response times for the N-back test was observed only among the cohort taking the test in the quiet environment first. The degree to which subjects understood instructions also appeared to be correlated with performance on the Simple and Complex test during the

Table 5. Spearman correlations and associated p-values of subjects' self-reported experience with the DETECT system and their overall performance on each test, stratified by environment and test order.

Test name	Variable	No visual distractions	Noise blocked	Understood instructions	Able to concentrate	Felt nervous
Noisy environment, first test						
N-Back	Overall score	$-0.11; p=0.63$	$-0.05; p=0.82$	$-0.23; p=0.31$	$-0.15; p=0.52$	$0.03; p=0.89$
	Response time	$0.26; p=0.26$	$0.08; p=0.72$	$0.17; p=0.46$	$-0.05; p=0.82$	$-0.13; p=0.56$
Selective Reminding	Overall score	$-0.30; p=0.20$	$-0.04; p=0.86$	$-0.31; p=0.18$	$-0.02; p=0.92$	$-0.09; p=0.71$
	Response time	$0.20; p=0.39$	$-0.16; p=0.51$	$0.01; p=0.97$	$-0.28; p=0.22$	$0.09; p=0.70$
Simple & Complex	Overall score	$0.05; p=0.81$	$-0.09; p=0.70$	$-0.15; p=0.50$	$-0.03; p=0.88$	$-0.38; p=0.09$
	Response time	$0.11; p=0.64$	$-0.48; p=0.03$	$0.15; p=0.53$	$-0.40; p=0.08$	$-0.16; p=0.50$
Quiet environment, first test						
N-Back	Overall score	$0.11; p=0.64$	$-0.04; p=0.87$	$-0.48; p=0.04$	$0.16; p=0.52$	$0.39; p=0.10$
	Response time	$0.17; p=0.48$	$0.05; p=0.84$	$0.46; p=0.04$	$0.08; p=0.75$	$-0.30; p=0.20$
Selective Reminding	Overall score	$0.27; p=0.26$	$0.11; p=0.66$	$0.05; p=0.83$	$0.00; p=1.0$	$0.08; p=0.76$
	Response time	$-0.07; p=0.76$	$-0.04; p=0.86$	$-0.27; p=0.26$	$0.13; p=0.58$	$0.14; p=0.58$
Simple & Complex	Overall score	$0.04; p=0.89$	$0.43; p=0.06$	$-0.01; p=0.96$	$-0.01; p=0.97$	$-0.11; p=0.65$
	Response time	$-0.25; p=0.30$	$0.28; p=0.24$	$0.08; p=0.75$	$0.13; p=0.58$	$-0.44; p=0.06$
Noisy environment, second test						
N-Back	Overall score	$0.04; p=0.86$	$0.02; p=0.94$	$-0.26; p=0.28$	$-0.26; p=0.28$	$0.35; p=0.15$
	Response time	$0.23; p=0.34$	$-0.16; p=0.50$	$0.14; p=0.57$	$0.25; p=0.30$	$0.05; p=0.84$
Selective Reminding	Overall score	$0.05; p=0.84$	$0.23; p=0.34$	$0.20; p=0.42$	$-0.20; p=0.40$	$-0.02; p=0.93$
	Response time	$0.03; p=0.90$	$-0.09; p=0.71$	$-0.15; p=0.55$	$0.31; p=0.20$	$0.23; p=0.35$
Simple & Complex	Overall score	$0.03; p=0.92$	$0.20; p=0.40$	$0.28; p=0.25$	$-0.03; p=0.90$	$-0.07; p=0.77$
	Response time	$-0.01; p=0.98$	$0.34; p=0.16$	$0.29; p=0.23$	$0.12; p=0.64$	$0.02; p=0.93$
Quiet environment, second test						
N-Back	Overall score	$-0.13; p=0.57$	$-0.04; p=0.87$	$-0.56; p=0.01$	$-0.20; p=0.39$	$-0.10; p=0.66$
	Response time	$0.29; p=0.20$	$-0.04; p=0.85$	$0.40; p=0.07$	$-0.02; p=0.92$	$-0.14; p=0.56$
Selective Reminding	Overall score	$0.01; p=0.96$	$-0.16; p=0.51$	$-0.03; p=0.91$	$-0.16; p=0.49$	$-0.02; p=0.92$
	Response time	$0.35; p=0.13$	$-0.12; p=0.62$	$0.16; p=0.51$	$-0.20; p=0.40$	$-0.46; p=0.04$
Simple & Complex	Overall score	$-0.01; p=0.99$	$-0.09; p=0.70$	$-0.47; p=0.03$	$-0.31; p=0.18$	$-0.22; p=0.33$
	Response time	$0.27; p=0.24$	$-0.07; p=0.75$	$0.08; p=0.73$	$-0.07; p=0.78$	$-0.46; p=0.03$

second exposure in the quiet environment. These findings emphasize the importance of using instructions that clearly articulate the DETECT™ testing process.

4. Discussion

Undiagnosed mTBI can result in long-term cognitive and emotional sequelae and even death. Most health care providers would agree that there is a tremendous need for a portable, rapid and sensitive tool for diagnosing mTBI. Our preliminary data using the DETECT™ system indicate that the hardware provides an adequate immersive environment for neuropsychological testing, even in an artificially produced noisy environment. A key design criterion was to create an immersive environment to exclude visual and audio distractions. Neuropsychological tests sensitive to mild TBI were modified to reduce test length and reduce the dependence on trained personnel. This permits rapid, sensitive neuropsychological testing in a portable arrangement. The prototype used in this study includes off-the-shelf components that have allowed us to test the concept of the DETECT™ immersive system at a relatively low cost. Such a device could be an effective way of diagnosing mTBI at the scene of injury. This system has great potential for use as a sideline assessment for concussion tool or in situations where a portable and easy-to-use screening tool is appropriate.

Ongoing research is comparing the DETECT™ system and previously validated paper and pencil neuropsychological tests in head injured patients, which will provide evidence concerning the sensitivity of the DETECT™ system for detecting cognitive deficits. This will allow us to test if the device is able to identify subtle cognitive deficits better than current assessment tools. The current study demonstrated the feasibility, usability, and immersive properties of the DETECT system for neuropsychological testing in situations that normally have visual and auditory distractions, thus establishing the potential for DETECT™ to be used as a novel assessment tool for mTBI in clinical practice.

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References

[1] Anonymous, 2002, *Injury Fact Book* (Atlanta: National Center for Injury Prevention and Control).

[2] Kelly, J.P., Nichols, J.S., Filley, C.M., Lillehei, K.O., Rubinstein, D. and Kleinschmidt-DeMasters, B.K., 1991, Concussion in sports. Guidelines for the prevention of catastrophic outcome. *JAMA*, **266,** 2867–2869.

[3] Cantu, R.C., 1998, Second-impact syndrome. *Clinics in Sports Medicine*, **17,** 37–44.

[4] Cantu, R.C. and Voy, R., 1995, Second-impact syndrome – a risk in any contact sport. *Physician and Sports Medicine*, **23,** 27.

[5] Englander, J., Hall K., Stimpson, T. and Chaffin, S., 1992, Mild traumatic brain injury in an insured population: subjective complaints and return to employment. *Brain Injury*, **6**(2), 161–166.

[6] Fann, J.R., Katon, W.J., Uomoto, J.M. and Esselman, P.C., 1995, Psychiatric disorders and functional disability in outpatients with traumatic brain injuries. *American Journal of Psychiatry*, **152,** 1493–1499.

[7] Gomez-Hernandez, R., Max, J.E., Kosier, T., Paradiso, S. and Robinson, R.G., 1997, Social impairment and depression after traumatic brain injury. *Archives of Physical Medicine & Rehabilitation*, **78**(12), 1321–1326.

[8] Jorge, R.E., Robinson, R.J., Arndt, S.V., Forrester, A.W., Geisler, F. and Starkstein, S.E., 1993, Comparison between acute- and delayed-onset depression following traumatic brain injury. *Journal of Neuropsychiatry & Clinical Neurosciences*, **5,** 43–49.

[9] van der Naalt, J., van Zomeren, A.H., Sluiter, W.J. and Minderhoud, J.M., 1999, One year outcome in mild to moderate head injury: the predictive value of acute injury characteristics related to complaints and return to work. *Journal of Neurology, Neurosurgery & Psychiatry*, **66,** 207–213.

[10] Stambrook, M., Moore, A.D., Peters, L.C., Deviaene, C. and Hawryluk, G.A., 1990, Effects of mild, moderate and severe closed head injury on long-term vocational status. *Brain Injury*, **4,** 183–190.

[11] Gronwall, D., 1976, Performance changes during recovery from closed head injury. *Proceedings of the Australian Association of Neurology*, **13,** 143–147.

[12] Gronwall, D. and Wrightson, P., 1974, Delayed recovery of intellectual function after minor head injury. *Lancet*, **2,** 605–609.

[13] Gronwall, D., 1989, Cumulative and persisting effects of concussion on attention and cognition. In H.S. Levin and H.M. Eisenberg (Eds) *Mild Head Injury* (New York, USA: Oxford University Press), pp. 153–162.

[14] Gronwall, D. and Wrightson, P., 1981, Memory and information processing capacity after closed head injury. *Journal of Neurology, Neurosurgery & Psychiatry*, **44,** 889–895.

[15] Buschke, H. and Fuld, P.A., 1974, Evaluating storage, retention, and retrieval in disordered memory and learning. *Neurology*, **24,** 1019–1025.

[16] Hugenholtz, H., Stuss, D.T., Stethem, L.L. and Richard, M.T., 1988, How long does it take to recover from mild concussion? *Neurosurgery*, **22,** 853–858.

[17] MacFlynn, G., Montgomery, E.A., Fenton, G.W. and Rutherford, W., 1984, Measurement of reaction time following minor head injury *Journal of Neurology, Neurosurgery & Psychiatry*, **47,** 1326–1331.

[18] McAllister, T., Saykin, A., Flashman, L., Sparling, M., Johnson, S., Guerin, S., Mamourian, A., Weaver, J. and Yanofsky, N., 1999, Brain activation during working memory 1 month after mild traumatic brain injury: A functional MRI study. *Neurology*, **53,** 1300–1308.

[19] McAllister, T.W., Sparling, M.B., Flashman, L.A., Guerin, S.J. and Saykin, A.J., 2000, Early plateau of brain activation on fMRI in response to increased working memory task difficulty one month after mild traumatic brain injury (MTBI). *Journal of Neuropsychiatry & Clinical Neurosciences*, **12,** 159–160.

[20] Battig, W.F. and Montague, W.E., 1969, Category norms of verbal items in 56 categories. A replication and extension of the Connecticut category norms. *Journal of Experimental Psychology*. **80**(3, Pt. 2), 1–46.