Development of a new virtual reality test of cognition: assessing the test-retest reliability, convergent and ecological validity of CONVIRT

Ben Horan¹, Rachael Heckenberg², Paul Maruff³ and Bradley Wright⁴*

Abstract

Background: Technological advances provide an opportunity to refine tools that assess central nervous system performance. This study aimed to assess the test-retest reliability and convergent and ecological validity of a newly developed, virtual-reality, concussion assessment tool, 'CONVIRT', which uses eye-tracking technology to assess visual processing speed, and manual reaction time (pushing a button on a riding crop) to assess attention and decision-making. CONVIRT was developed for horse jockeys, as of all sportspersons, they are most at risk of concussion.

Methods: Participants (N = 165), were assessed with CONVIRT, which uses virtual reality to give the user the experience of riding a horse during a horserace. Participants were also assessed with standard Cogstate computer-based concussion measures in-between two completions of the CONVIRT battery. The physiological arousal induced by the test batteries were assessed via measures of heart rate and heart rate variability (LF/HF ratio).

Results: Satisfactory test-retest reliability and convergent validity with Cogstate attention and decision-making subtests and divergent validity in visual processing speed measures were observed. CONVIRT also increased heart rate and LF/HF ratio, which may better approximate participant arousal levels in their workplace.

Conclusions: CONVIRT may be a reliable and valid tool to assess elements of cognition and CNS disruption. The increased ecological validity may also mean better informed ‘return-to-play’ decisions and stronger industry acceptance due to the real-world meaningfulness of the assessment. However, before this can be achieved, the sensitivity of the CONVIRT battery needs to be demonstrated.

Keywords: VR, Eye-tracking, Concussion, Mild traumatic brain injury, Assessment

Background

Concussion amongst sportspersons is a worldwide concern due to both its prevalence and relationship with lifelong disease states [1]. Consequently, there has been substantial development in concussion management programs for athletes who play sports where the risk of concussion is high. Such strategies include recognition of risk factors, removal from play of injured athletes, careful management of return to play, and rule changes and education. In these strategies, the accurate assessment of cognition is crucial to both identifying the central nervous system (CNS) dysfunction that follows concussion and its resolution with time as athletes are managed toward their return to play [2]. Of all sportspersons, jockeys have the highest rate of concussion and the highest fatality rate (per minute of participation [3]).
For example, jockeys fall 1 out of every 240 rides [4] and are 5 times more likely than an Australian Rules footballer to experience a concussion [5]. Therefore, concussion management programs that use cognitive assessment have been established in this group [6].

While multiple cognitive tests have been validated for use in concussion management programs, as newer research and emerging technologies provide important information and capabilities to guide refinement, there remains a need to continue to improve such assessment. For example, recent studies have found that in addition to cognition, careful analyses of ocular motor functions may provide insight into concussion related CNS dysfunction [7, 8]. In the technology domain, consumer grade virtual reality Head Mounted Displays (HMDs) have recently emerged providing the ability to readily immerse users in high quality virtual environments [9]. Eye-tracking, while not new to research studies, is now starting to be integrated into virtual reality headsets providing new opportunities in a range of domains.

There are three different types of ocular movements. Smooth pursuits are slow, voluntary, controlled movements that track a moving stimulus via speed and fixation [10]. Vergence movements are simultaneous and maintain fusion on objects near or far [11]. Saccades are rapid, ballistic eye movements that shift the gaze to new areas of interest and help bring a target into focus [12]. When a stimulus suddenly appears in the visual field, saccadic movement occurs voluntarily or reflexively [13]. Saccades require complex coordination of neural circuitry in different brain regions (i.e., frontal lobe, basal ganglia, cerebellum), and therefore, act as a sensitive indicator of potential dysfunction in these areas [12]. Measurement of saccadic movement may be a sensitive tool for assessment of functional and structural cognitive impairment post-concussion which is lacking in clinical assessment of cognitive abilities [14]. Finally, compared to standard tests of cognition, such measurements are less likely to be influenced by individuals’ intellectual abilities, self-report, fatigue and/or practice effects [11, 15, 16].

Saccadic eye movements are associated with visual attention, visual discrimination [17, 18], working visual memory, decision-making [19], and visual processing speed [20]. Given these areas of cognition are often assessed in concussion management protocols, a measure of saccadic movement could enhance the sensitivity of such concussion assessments [11, 13, 21].

Recent research has highlighted that eye-tracking technology may be a useful adjunct to standard neuropsychological tests for mild traumatic brain injury (mTBI), but endeavours to include the technology have been limited by an inability to get such technology to function reliably and validly beyond laboratory settings [14]. Laboratory based equipment is cumbersome, involves adjusting camera positions and chin rests and as such, may compromise the reliability of such assessment. Recent advances in camera-based eye-tracking technology within wearable headsets however, have led to high precision tests that are reliable and valid [22, 23]. Using eye-tracking technology within a virtual-reality environment adds a further step towards ‘normalising’ the experience of such testing for the user.

While the scientific principles that guide concussion management programs are consistent across the different sports in which they are used, understanding better the specific context of cognitive testing within individual sports may result in a greater sensitivity to concussion related cognitive impairment. Current virtual-reality technologies enable a high level of visual and auditory immersion in a particular environment and task. As such, concussion testing that incorporates virtual-reality as well as the specific sporting content, may improve user acceptance and foster better adherence and compliance as athletes can better appreciate the relevance of the assessment to the optimal execution of their own sport. In the context of neuropsychological testing this principle is termed ecological validity. Specifically, this form of ecological validity is known as verisimilitude – which refers to the similarity of the instrument to relevant environmental behaviours [24].

We have developed a virtual-reality (VR) concussion assessment battery ‘CONVIRT’ that assesses components of attention, decision-making, and visual processing speed using assessments of manual simple and choice reaction time and saccadic reaction time. CONVIRT has the user complete the cognitive tests while riding a horse during a horserace in a virtual environment. VR paradigms have been shown to elicit heightened physiological arousal [25, 26]. When this information is considered alongside research which suggests that higher physiological arousal during cognitive testing was associated with poorer performance among jockeys [27] and students [28], it may be important to assess cognition when the athlete’s physiological arousal better approximates that required during their sport. Additionally, CONVIRT incorporates standard ‘distractors’ such as spectator sounds and movement of horses within the dynamic testing environment. These distractions are however, held constant across testing sessions.

The development of new measures for use in clinical settings must begin with understanding their performance in laboratory conditions. These studies focus on establishing psychometric test characteristics such as reliability and validity [29]. In addition, for cognitive tests designed to be given repeatedly it is crucial to know their stability over time. Furthermore, because the use of tests to manage CNS injury in the area of interest requires strong understanding of how performance may
change (or ideally remain stable) in the absence of any true CNS impairment or CNS injury, it is necessary in the first instance that such estimates be obtained from healthy adults tested at intervals where the potential for any true or important changes in CNS state (for example, arising from fatigue, drug use, pain) are very small. Consequently, the aim of this study was to test the reliability of CONVIRT assessments over short retest intervals and also to assess convergent (simple and choice-reaction time) and divergent validity (saccadic reaction time) with comparable neuropsychological tests of concussion. In this study we used a sample of university students to assess the psychometric properties of CONVIRT. Once these properties are demonstrated we plan to test the sensitivity of the CONVIRT battery using a pre-post prospective study of concussion with a sample of jockeys. Finally, we aimed to determine if compared to the standard computer-based testing, CONVIRT elicited higher physiological arousal.

**Methods**

**Participants**

Participants (N=165, females=84) were Australian university students who were approached using a script and invited to engage in the research project. Participants (Mage = 22.91, range 18–34 years, SD = 3.50) were included if they were currently full-time students (academic stress assessed in separate study) and could read English, and excluded if they were currently unwell, had ongoing health problems, considered themselves physically fragile, or had received a concussion in previous 6 months. Given the student sample was healthy, with a comparable age-range, free from concussion, and similar to jockeys [27], are known to be highly stressed [28, 30], they served as an ideal proxy sample. Based on a power analysis for biserial correlation using G*Power 3 with a conservative medium effect of $p = .30$ (Falleti et al. [31] report very high effect sizes with a similar design), and power set at .80, an N of 64 was required to detect an association at $p = .05$. The sample size was larger than required for the present study, as some of the data will be used to answer other research questions where more statistical power is required. Participants (mean BMI = 24.98, SD = 5.32) provided written informed consent in line with institutional ethics (HEC S17–117) and were compensated for their time with a double cinema voucher.

**Materials**

The Cogstate battery

Three computerised tests from the Cogstate battery (Cogstate Research software; Version 6; Cogstate Limited, 2011) were included; the Detection task (DET), the Identification task (IDN), and the Groton Maze Chase test (GMCT) and administered using a 14-in. laptop. The individual tasks are designed to test a specific area of cognition over repeated sessions [32] and are routinely used to assess change post-concussion in elite, contact sports to help inform return to play decisions [33, 34].

**Attention**

The DET assesses psychomotor function through a simple reaction time paradigm. The participant is presented with a playing card that is face-down in the centre of the computer screen. The playing card is then turned face up and the participant must press the appropriate response key as quickly as possible after the card flips. The DET task ends after 35 correct responses. In healthy participants, the average completion time for this task is 3 min.

**Decision making**

The IDN is a choice reaction time test that measures psychomotor speed and decision making. The participant is again presented with a face-down card but is then instructed to indicate if the card is red or black as quickly as possible when the card is turned face up. The IDN task ends after 30 correct responses. In healthy participants the task takes approximately 3 min to complete.

**Visual processing speed**

The GMCT is a timed 30-s task designed to measure simple visuomotor processing speed. In this task, participants are required to follow a moving, coloured tile through a $10 \times 10$ grid, as quickly as possible using the computer mouse cursor.

The DET and IDN reaction times are recorded in milliseconds. These types of tests are known to produce positively skewed distributions and are routinely, statistically transformed using a natural logarithm to better represent a normal curve distribution [35, 36]. The GMCT score represents the average number of moves per second on the task. Therefore, low scores represent better performance on the IDN and DET tests and high scores represent better performance on the GMCT.

The Cogstate battery has demonstrated high test-retest reliability and limited practice effects at 10-min, one-week, and one-month intervals. For the DET task, intraclass correlations were 0.84 and 0.83 for the two 10-min intervals and 0.94 and 0.73 for the one-week and month intervals. The IDN task showed similar intraclass correlations, specifically 0.38, and 0.55, for the two 10-min intervals and 0.81 and 0.71 for the one-week and month intervals [36]. The DET and IDN have also demonstrated good convergent validity with conventional pencil and paper neuropsychological tests.
The CONVIRT battery
The CONVIRT battery comprises the CONVIRT VR application, FOVE 0 Eye Tracking VR Headset, and customised riding crop with button and wireless connectivity all running through a gigabyte P35 laptop (Fig. 1).

The FOVE 0 Eye Tracking VR Head Mounted Display (HMD) provides built-in eye tracking functionality. The HMD displays the virtual environment to the subject as well as tracking their head rotation and direction of their gaze. The position and orientation of the HMD is tracked by an Inertial Measurement Unit (IMU) internal to the HMD as well as by an external tracking camera.

The CONVIRT application runs on a Gigabyte P35 laptop. The laptop is running 64-bit Windows 10 Home OS, has an i7-6700HQ CPU, 16Gb of DDR4 RAM and a GeForce GTX 1070 graphics card. The laptop is capable of running the CONVIRT application and the FOVE headset at 70 frames per second (FPS) for the display and 120 fps for eye tracking sensors, in order to provide the most accurate results. These are the highest update rates for the FOVE headset.

The CONVIRT VR application is built in the Unity gaming engine and runs on the 64-bit Windows 10 operating system. The application places the user on a virtual horse running on a racecourse modelled to be similar to a professional horse racing track. The tool consists of three tests. Each test presents floating shapes in front of the user to which they must respond to in a manner dependant on the test being conducted. The shapes are positioned at different points along an invisible 180-degree arc in front of the virtual horse and give the experience of being in extra-personal space. The targets (and distractors) are on a vertical plane in front of the user at a distance of 1.5 m from the user’s head, and the arc centrepoint is directly in front of the user’s head, and the arc has a radius of 0.5 m.

The design of the environment in all tests is suitable for those who are colour-blind (Fig. 2). All tests have instructions embedded to the user’s view and have a practice trial before each test. Participants are seated in a fixed chair during testing.

Pilot testing
The CONVIRT battery was trialled with professional jockeys (n = 7) and jockey coaches (n = 3) to ensure the virtual environment mirrored that of a professional horserace. Slight modifications to the gait of the virtual horses were recommended and then implemented. None of the jockeys or coaches reported any nausea or motion sickness. Careful consideration was given to following best practice design with a specific focus on reducing sensory-conflict and latency that are well known contributors to sickness when using VR [37]. To minimise impact from sensory conflict between vision and vestibular systems, the horses and user move along the track at a constant velocity of 20 km/h and accelerations are avoided. Modern headsets have significantly decreased latency times and in the design of CONVIRT, consideration was given to allow the frame rate of the virtual experience to run at the maximum possible framerate allowing the headset to have minimal delays (lowest latency) in updating the visual information displayed to the user. The events inside the VR experience (e.g. bobbing due to horse running motion) do not alter the height of the user’s view within VR while riding down the virtual track. The user however can turn their head to view the track around them, or also lower or raise their head while sitting in the chair. This motion is
limited to the ability of the user to hunch down or stretch up and is rather minimal relative to the sizes of the objects in the virtual scene, as well as the distance from the user’s head to the invisible plane where the targets (and distractors) appear. Early feedback from jockeys and their coaches confirmed that CONVIRT adequately represented a horse race experience.

**Visual processing speed**

The first test is an eye tracking test that measures a subject’s saccadic reaction time (SAC). When the test starts the subject needs to stare at a grey circle, positioned in the centre of the above mentioned 180-degree arc, for a duration of 2 sec. After this time the grey circle will disappear, and a blue circle will appear somewhere on the arc (Fig. 2). The subject needs to look at the blue circle with both eyes, as quickly as possible. When the subject’s gaze converges on the blue circle it will ‘explode’ (visual representation of disintegration accompanied by auditory explosion sound) and then disappear and the grey circle will reappear and the process is repeated when the participant holds their gaze on the grey circle for 2 sec. This process continues until the subject has looked at 35 blue circles. The position of blue circles presented at 13 degrees in the left hemisphere of the arc, are mirrored in the right hemisphere (17 each side). One blue circle is presented in the midline above the grey circle. The time it takes for the subject to move their gaze from the grey circle to the blue circle is recorded and additionally, we measured the time taken to move 50% towards the target. This portion of the saccade will capture the response latency (the time taken to initiate the saccade), which is approximately 200 ms. [38] and a component of acceleration towards the target. We chose not to use the complete time to converge on the target as this would incorporate a variety of more complex neural processes including deceleration prior to reaching the target, adjustments to improve gaze accuracy, and the fact that saccades only account for approximately 90% of the movement between the eye and the target [38]. It was this measure of SAC that was used in all subsequent analyses.

**Attention**

The second test (DET\textsuperscript{VR}) evaluates a subject’s manual simple reaction time to a stimulus. An orange triangle randomly appears in front of the user at a point on the arc. Once the user detects a triangle, they need to press the button on the riding crop resulting in the triangle disappearing for differing durations (ranging from 1 s. to 2.37 s.). Similar to the Cogstate DET test, the test lasts for 120 s and 35 triangles are displayed to the subject. The reaction time is recorded along with any presses of the push button when the triangle is not present, i.e., false positives.

**Decision-making**

The third test (IDN\textsuperscript{VR}) assesses choice reaction time. This test is similar to the previous test in that the user must respond using the riding crop button to a shape appearing. The subject needs to respond to an orange circle appearing and must not respond to a blue triangle or blue circle appearing. Similar to the Cogstate IDN test, the test lasts for 120 s and in that time 31 shapes are displayed to the subject. The reaction time of the subject is recorded along with any incorrect responses.

**Heart rate variability (HRV)**

The measures of heart rate (HR) and HRV were used to assess if the CONVIRT experience was more physiologically
arousing than the seated computer-based Cogstate testing. Heightened sympathetic arousal on both HR and HRV measures is indicated by higher scores. HRV is an indirect measure of the autonomic nervous system and may reflect the push-pull relationship between the sympathetic and parasympathetic nervous system [39]. The present study measured the low frequency (LF) to high frequency (HF) ratio of spectral HRV. An increased LF/HF ratio is associated with increased stress [40]. It has been suggested that a higher LF/HF ratio reflects sympathetic dominance while decreases correspond to parasympathetic dominance [41]. The measures of heart rate (beats per min) and LF/HF were used to assess if autonomic arousal differed during CONVIRT and Cogstate testing. Consecutive RR intervals were recorded using a wireless heart rate monitor (RS800CX; Polar, Finland). The Polar heart rate monitors have been shown to produce electrocardiography comparable measures of RR-interval with derived time domain HRV [42]. After removing non-sinus RR-intervals, consecutive RR-intervals were analysed using customised commercial software (LabVIEW 2016; National Instruments, UK) to determine short-term HRV in the time domain for 5-min. Epochs in user-selected time blocks.

Procedure
Upon arrival to the lab, participants provided informed consent. They were then given instructions on how to fit the HR monitor and privacy to do so. Once fitted, participants completed a questionnaire pack (data not reported in this study), which included demographic information, as well as height and weight to enable to calculation of body mass index (BMI). BMI is routinely entered as a covariate in analyses involving HRV. Recording of HR and the LF/HF ratio began immediately and continued throughout the experiment.

Baseline phase ($M = 8.58$ mins, $SD = 2.61$ mins, range $=5–24$ min)
Participants sat at a table with the equipment for the CONVIRT and Cogstate tests placed in front of them. Participants completed their questionnaires. The baseline period was used as a means of collecting data, but also to minimise the impact of anticipatory arousal on test performance. Strong anticipatory physiological responses before Cogstate testing has been observed in similar studies using these cognitive measures with measures of HRV [28].

CONVIRT 1 ($M = 15.45$ mins, $SD = 4.25$ mins, range $=11–25$ min)
Participants were fitted with the FOVE 0 Eye Tracking VR Headset and given the customised riding crop. Participants completed the CONVIRT tests in the order they are presented above. Each test involved the participant receiving instructions on screen and the opportunity to complete a practice trial to ensure they were familiar with the assessment requirements and the use of equipment before the participant completed the test.

Cogstate ($M = 8.08$ mins, $SD = 1.72$ mins, range $=5–17$ min)
The participants then completed the Cogstate battery in a consistent order (i.e., DET then IDN then GMCT). Participants were provided with on-screen instructions and practice trials before each task to ensure they understood the requirements of each task. Practice trials are routinely conducted before each task in the Cogstate battery [36].

CONVIRT 2 ($M = 12.40$ mins, $SD = 3.22$ mins, range $=6–27$ min)
Participants were directed to complete the CONVIRT tests for a second time. The procedure was the same as the CONVIRT 1 phase.

Data analysis
Repeated measures MANCOVA (age, BMI covariates) was used to assess if participants differed in heart rate or HRV when using the CONVIRT compared to Cogstate tests. Intra class correlation (ICC) was used to assess the test-retest reliability of CONVIRT and convergent and divergent validity with comparable Cogstate measures. Convergent and divergent construct validity were examined using Pearson’s correlation coefficient and were evaluated using the guidelines (correlation levels: negligible $= 0.00–0.19$, weak $= 0.20–0.39$, moderate $= 0.40–0.59$, strong $= 0.60–0.79$, very strong $= 0.80–1.00$). Convergent and divergent validity was classified if $r > 0.70$ or $< 0.30$ respectively [43]. ICC values were interpreted as $> 0.75 = excellent$, $0.40$ to $0.75 = fair to good$, and $< 0.40 = poor$ [44].

Results
Data management
In line with the transformed Cogstate variables, a natural logarithm transformation was applied to the three CONVIRT measures. There was no missing data and the assumptions for parametric testing for ANCOVA and intra class correlation were satisfied [45].

Analyses
The mean and standard deviation for each of the cognitive tests (Table 1) and measures of HR and LF/HF across each phase of the study (Table 2) are reported. A repeated measures MANCOVA was used to assess if participant HR or the LF/HF measures of autonomic reactivity differed between CONVIRT and Cogstate testing paradigms after controlling for age, gender and BMI.
The MANCOVA revealed differences in HR and LF/HF across the CONVIRT and Cogstate testing $F(4, 160) = 10.59, p < .001$. Using a Bonferroni adjustment, the criterion alpha level was .025 for the two comparisons made for each measure of physiological arousal. Participants had higher HR and LF/HF ratios in all cases except for the LF/HF comparison between Cogstate and the first CONVIRT test, although this comparison trended in the anticipated direction (Table 3). The effect sizes were all small by Cohen’s convention where $d$ values of .20, .50 and .80 correspond with small moderate and large effects, respectively [46].

The final set of analyses assessed the test-retest reliability (average 8.08 min. apart) of the CONVIRT measure and the convergent validity of the CONVIRT tests with comparable Cogstate measures (Table 4). The approximate 10 min. Test-retest reliability of the CONVIRT measures were excellent for the DET and IDN and SAC measures [44]. The convergent validity of the CONVIRT DET and IDN was acceptable with the Cogstate DET and IDN tests (both > 0.70), and the low association between the SAC and GMCT (< 0.30) tests [43] suggests divergent validity between these measures (Table 4).

**Discussion**

The CONVIRT tests demonstrated high test-retest reliability and satisfactory convergent and divergent validity with related subtests from the Cogstate battery. CONVIRT also elicited greater physiological responses when compared to the Cogstate battery.

Establishing the test-retest reliability of cognitive tests used to assess sport-related concussion is important given that these tests are used to compare baseline performance against post-concussion performance. The DET and IDN task have demonstrated satisfactory levels of reliability with intraclass correlation coefficients reaching .60 or above [36, 47], which is said to be the accepted minimum for making clinical decisions [48]. The CONVIRT tool demonstrated even larger intraclass correlation coefficients with each task exceeding .75, which is typically considered the acceptable level for test-retest reliability [48, 49].

CONVIRT also demonstrated satisfactory convergent validity with two of the subtests correlating with the conceptually matched Cogstate subtests. Specifically, the DETLR and the IDNLR at both timepoints were moderately correlated with the DET and IDN, respectively. This is in line with what would be expected given that both tasks are assessing attention and decision-making via reaction times.

The SAC and GMCT tasks showed only a small correlation. This is likely due to the substantive differences in measurement of visual processing speed. The SAC uses eye tracking technology to assess saccade reaction time. In contrast, the GMCT infers visual processing speed from the participants ability to follow a target using a computer mouse cursor. Measures of saccadic

**Table 1** Average speed of reaction to each Cogstate and CONVIRT test

| Variable | M    | SD  |
|----------|------|-----|
| Cogstate | DET  | 2.53| .08 |
|          | IDN  | 2.68| .06 |
|          | GMCT | 1.67| .29 |
| CONVIRT  | DETLR | 2.44| .06 |
|          | DETLR | 2.45| .05 |
|          | IDNLR | 2.56| .06 |
|          | IDNLR | 2.55| .06 |
|          | SAC   | 2.44| .09 |
|          | SAC   | 2.43| .06 |
|          | Note. For the GMCT the mean values represent moves per sec. The mean values for all other tests were in milliseconds and have been transformed by natural logarithm

| Comparison | Cohen d | p   |
|------------|---------|-----|
| HR         | Cogstate-CONVIRT 1 | .24  | <.001 |
|           | Cogstate-CONVIRT 2 | .15  | .007  |
| LF/HF      | Cogstate-CONVIRT 1 | .08  | .241  |
|           | Cogstate- CONVIRT 2 | .28  | .005  |

| Comparison | r     | p    |
|------------|-------|------|
| DETLR 1 - DETLR 2 | .90  | < .001 |
| DETLR 1 - DET (Cogstate) | .59  | < .001 |
| DETLR 2 - DET (Cogstate) | .58  | < .001 |
| IDNLR 1 - IDNLR 2 | .88  | < .001 |
| IDNLR 1 - IDN (Cogstate) | .73  | < .001 |
| IDNLR 2 - IDN (Cogstate) | .75  | < .001 |
| SAC 1 - SAC 2 | .76  | < .001 |
| SAC 1 - GMCT (Cogstate) | .26  | .027  |
| SAC 2 - GMCT (Cogstate) | .26  | .022  |

**Table 3** Comparison of HR and LF/HF ratio between Cogstate and CONVIRT 1 and CONVIRT 2

**Table 4** Intra Class Correlations between each test for CONVIRT 1 and 2, and Cogstate
responsibility may be compromised by stress. In future research, ships. For university students, performance on academic battery, may offer additional insights into these relations.

VIRT tool, which is more arousing than the Cogstate tests for both students [28] and jockeys [27]. The CONVIRT was designed specifically to minimise nausea occurring using best practice and design guidelines for VR including a specific focus on minimising vision-vestibular system mismatch by using constant velocity and avoiding accelerations and keeping the headset frame rate at maximum (and headset visual latency at the minimum). We can also report that none of the participants reported nausea or asked the testing to be stopped. These experiences are consistent with what was observed in our pilot testing with jockeys.

The CONVIRT test offers several advantages over computer-based testing. For example, the dynamic environment resembles the workplace, but it requires less interaction with the tester, ensures stable light and sounds, and as the SAC test assesses a mixture of exogenous and endogenous processes, the impact of practice effects is reduced.

The current study demonstrates the test-retest reliability and convergent validity of the CONVIRT tool. However, future studies are planned to assess the test-retest reliability over longer time-intervals and to test the sensitivity of this battery in detecting changes in cognitive abilities. Additionally, in the present study, visual processing speed was measured using the time elapsed to 50% of the total distance to the target stimulus. We have outlined that capturing data from the final 50% of the ocular movement towards the target may include more complex neuronal processes (e.g., deceleration, accuracy adjustments etc.). Our focus was on the speed of saccade and not accuracy, and this aligns with decisions made for other neurocognitive assessment batteries [32]. That said, in future research, an analysis of the final segments of the gaze-to-target time and measures of vergence may also be useful in assessing CNS performance post-concussion. Finally, we did not assess the time lag associated with using the Bluetooth device for measures of simple and choice reaction time in the CONVIRT battery, we will run this experiment in the future. However, as the speed and variability of performance on these tests was the same or lower than the Cogstate computer-based measures (Table 3), this is unlikely to be a substantive issue.

The CONVIRT test offers several advantages over computer-based testing. For example, the dynamic environment resembles the workplace, but it requires less interaction with the tester, ensures stable light and sounds, and as the SAC test assesses a mixture of exogenous and endogenous processes, the impact of practice effects is reduced.

Conclusions

Jockeys are at very high risk of concussion and decisions about when they are safe to return to ride post-concussion are guided by measures of their cognitive function. However, as the current measures of cognitive performance for jockeys have low ecological validity, this may compromise the decisions made using such measures.

Ensuring that jockeys have regained their pre-concussion cognitive abilities prior to re-engaging with the sport is vital in protecting them from a heightened risk of falling [4] and injury. The CONVIRT battery appears to incorporate reliable and ecologically valid measures of attention, decision-making and visuomotor processing speed, but future assessments are required to assess the sensitivity of the tool and also if these findings generalise to a sample of jockeys. Our findings suggest that the added visual and auditory distractors in the virtual environment improve the ecological validity of the testing without impacting the reliability or construct
validity of measurements. Given that these high levels of reliability and validity can be obtained in virtual reality without inducing sickness suggests that CONVIRT may prove to be an important adjunct to standard computerised neuropsychological testing.

Abbreviations
LF: Low frequency; HF: High frequency; HMMD: Head mounted display; CNS: Central nervous system; mTBI: Mild traumatic brain injury; VR: Virtual reality; DET: Detection test; IDN: Identification test; GMCT: Groton maze chase test; SAC: Saccadic reaction time; DET<sup>13</sup>: CONVIRT detection test; IDN<sup>13</sup>: CONVIRT identification test; IMU: Inertial measurement unit; HRV: Heart rate variability; FPS: Frames per second; BMI: Body mass index; ICC: Intra-class correlation coefficient; BPM: Beats per minute; ms: Milliseconds; HR: Heart rate

Acknowledgements
Stephen Smilevski (Deakin University) undertook the software development of the CONVIRT tool.

Authors’ contributions
BH contributed the first draft and subsequent revisions of the drafts as well as contributing to the research design and production of Figures. RH assisted with drafting the paper and final formatting. PM contributed to the research design, the draft and revisions of the paper. BW completed the first and final draft of the paper, oversaw the collection of data and conducted all statistical analyses. All authors have read and approved the manuscript.

Funding
N/A

Availability of data and materials
The data for all analyses are available in the Open Science Framework repository at https://osf.io/g8ps5/

Ethics approval and consent to participate
Participants provided written informed consent in line with La Trobe University ethics approval (HEC S17–1 17).

Consent for publication
Written informed consent was obtained from the research assistant for publication of this case report and any accompanying images. A copy of the written consent is available for review by the Editor of this journal.

Competing interests
BW and BH hold intellectual property over the CONVIRT battery. PM is employed by the company (Cogstate Ltd., Melbourne, Australia) that distributes the computer-based cognitive battery that was used in this study.

Author details
1 School of Engineering, Deakin University, Geelong, VIC 3216, Australia. 2 School of Psychology and Public Health, La Trobe University, Wodonga, Victoria 3690, Australia. 3 The Florey Institute, The University of Melbourne, Parkville, VIC 3052, Australia. 4 School of Psychology and Public Health, La Trobe University, Bundoora, Victoria 3086, Australia.

Received: 26 February 2020 Accepted: 5 June 2020
Published online: 12 June 2020

References
1. Khurana VG, Kaye AH. An overview of concussion in sport. J Clin Neurosci. 2012;19(1):1–11. Available from: https://doi.org/10.1016/j.jocn.2011.08.002.
2. McCrea M, Guskiewicz KM, Randolph C, Barr WB, Hammeke TA, Marshall SW, et al. Effects of a symptom-free waiting period on clinical outcome and risk of re-injury after sport-related concussion. Neurosurgery. 2009;65(5):SB2–3.
3. Turner M, McCrody P, Halley W. Injuries in professional horse racing in Great Britain and the Republic of Ireland during 1992–2000. Br J Sports Med. 2002;36(August):403–9.
4. Hitchens PL, Blizzard CL, Jones G, Day LM, Fell J. The incidence of race-day jockey falls in Australia, 2002–2006. Med J Aust. 2009;190(2):83–6.
5. Orchard J, Seward H, Orchard J. AFL injury report. AFL Reports; 2014. p. 1–26.
6. Turner M, Balendra G, McCrody P. Payments to injured professional jockeys in British horse racing (1996-2006). Br J Sports Med. 2008;42(9):763–6.
7. Anزالونi AJ, Bluett D, Case T, McGuffin T, Pollard K, Garrison JC, et al. A positive vestibular/ocular motor screening (VOMS) is associated with increased recovery time after sports-related concussion in youth and adolescent athletes. Ann J Sports Med. 2017;45(2):474–9.
8. Ellis MJ, Cordingley D, Vis S, Reimer K, Pt BMR, Leiter J, et al. Vestibulo-ocular dysfunction in pediatric sports-related concussion. J Neuropsychiatr Pediatr. 2015;16(3):248–55.
9. Salomoni P, Prandi C, Rocchetti M, Casanova L, Marchetti L, Marfia G. Diegetic user interfaces for virtual environments with HMDs: a user experience study on oculus rift. J Multimodal User Interfaces. 2017;11(2):173–84.
10. Hunt AW, Mah K, Reed N, Engel L, Keyntight M. Oculomotor-based vision assessment in mild traumatic brain injury: a systematic review. J Head Trauma Rehabil. 2016;31(4):252–61.
11. Taghdiri F, Varriano B, Tartaglia MC. Assessment of oculomotor function in patients with Postconcussion syndrome: a systematic review. J Head Trauma Rehabil. 2017;32(5):E55–65.
12. Ramat S, Leigh RJ, Zee DS, Optican LM. What clinical disorders tell us about the neural control of saccadic eye movements. Brain. 2007;130(1):10–35.
13. Sussman ES, Ho AL, Pendlharkar AV, Ghajar J. Clinical evaluation of concussion: the evolving role of oculomotor assessments. Neurosurg Focus. 2016;40(4):1–7.
14. Maruta J, Suh M, Niggi SN, Mukherjee P, Ghajar J. Visual tracking synchronization as a metric for concussion screening. J Head Trauma Rehabil. 2010;25(4):293–305.
15. Cifu DX, Wares JR, Hoke KW, Wetzel PA, Gitchel G, Carne W. Differential eye movements in mild traumatic brain injury versus normal controls. J Head Trauma Rehabil. 2015;30(1):21–8.
16. Heitger MH, Jones RD, MacLeod AD, Snell DL, Frampton CM, Anderson TJ. Impaired eye movements in post-concussion syndrome indicate suboptimal brain function beyond the influence of depression, malingering or intellectual ability. Brain. 2009;132(10):2850–70.
17. Cripps AE, Livingston SC. Visuo-motor processing impairments following concussion in athletes. J Athl Enhanc. 2015;4:1–6.
18. D’Amico NR, Mormile ME, Ake KM, Grimes KE, Powell DW, Reed-Jones RJ, et al. Assessment of anti-saccades within 24 to 48 hours post-concussion. Med Sci Sport Exerc. 2016;48(1):50.
19. Hutton SB. Cognitive control of saccadic eye movements. Brain Cogn. 2008;68(3):327–40.
20. Kirchner H, Thorpe SJ. Ultra-rapid object detection with saccadic eye movements: visual processing speed revisited. Vis Res. 2006;46(11):1762–76.
21. Sneijere N, Deman W, Patricios J, Weisman KE. Eye tracking technology in sports-related concussion: A systematic review and meta-analysis. Physiol Meas. 2018;39(12):127R01.
22. Bott N, Madero EN, Glenn J, Lange A, Anderson J, Newton D, et al. Device-embedded cameras for eye tracking-based cognitive assessment: validation with paper-pencil and computerized cognitive composites. J Med Internet Res. 2018;20(7):1–10.
23. Semmelmann K, Weigelt S. Online webcam-based eye tracking in cognitive science: a first look. Behav Res Methods. 2018;50(2):451–65.
24. Franzen MD, Wilhelm KL. Conceptual foundations of ecological validity in neuropsychological assessment. In: Sbordone RJ, Long CJ, editors. Ecological assessment in mild traumatic brain injury: a systematic review. J Head Trauma Rehabil. 2016;31(4):252–61.
25. Parsons TD, Courteney CG, Dawson ME. Virtual reality Stroop task for assessment of supervisory attentional processing. J Clin Exp Neuropsychol. 2013;35(8):812–26.
26. Parsons TD, Risso AA, Courteney CG, Dawson ME. Psychophysiology to assess impact of varying levels of simulation fidelity in a threat environment. Adv Human-Computer Interact. 2012;2012:1–9.
27. Landolt K, Maruff P, Horan B, Kingsley M, Kinsella G, O’Halloran PD, et al. Chronic work stress and decreased vaginal tone impairs decision making and reaction time in jockeys. Psychoneuroendocrinology. 2017;84(May):151–8.
28. Kuhnell R, Whitwell Z, Arnold S, Kingsley MIC, Hale, MW, Wahrendorf M, et al. Assessing the association of university stress and physiological reactivity with decision-making among students. Stress. 2020;23(2):136–43.
29. White SA, van den Broek NR. Methods for assessing reliability and validity for a measurement tool: a case study and critique using the WHO haemoglobin colour scale. Stat Med. 2004;23(10):1603–19.

Page 9 of 10
Horan et al. BMC Psychology (2020) 8:61
30. Wege N, Li J, Muth T, Angerer P, Siegrist J. Student ERI: Psychometric properties of a new brief measure of effort-reward imbalance among university students. J Psychosom Res. 2017;94:64–7.
31. Falleti MG, Maruff P, Collie A, Darby DG, McStephen M. Qualitative similarities in cognitive impairment associated with 24 h of sustained wakefulness and a blood alcohol concentration of 0.05%. J Sleep Res. 2003;12:265–74.
32. Collie A, Maruff P, Darby DG, McStephen M. The effects of practice on the cognitive test performance of neurologically normal individuals assessed at brief test-retest intervals. J Int Neuropsychol Soc. 2003;9(3):419–28.
33. Makdissi M, Collie A, Maruff P, Darby D, Bush A, McCrory P, et al. Computerised cognitive assessment of concussed Australian rules footballers. Br J Sports Med. 2001;35(5):354–60.
34. Makdissi M, Darby D, Maruff P, Ugoni A, Brukner P, McCrory PR. Natural history of concussion in sport. Am J Sports Med. 2010;38(3):464–71.
35. Anastasi A, Urbina S. Psychological testing. 7th ed. Prentice Hall/Pearson Education: Upper Saddle River; 1997.
36. Falleti M, Maruff P, Collie A, Darby D. Practice effects associated with the repeated assessment of cognitive function using the CogState battery at 10-minute, one week and one month test-retest intervals. J Clin Exp Neuropsychol. 2006;28(7):1095–112.
37. Porcino TM, Clua E, Trevisan D, Vasconcelos CN, Valente L. Minimizing cyber sickness in head mounted display systems: design guidelines and applications. In: In 2017 IEEE 5th international conference on serious games and applications for health (SeGAH); 2017. p. 1–6. IEEE.
38. Orian De Xivry JJ, Lefèvre P. Saccades and pursuit: two outcomes of a single sensorimotor process. J Physiol. 2007;584(1):11–23.
39. Task Force of the ES. Heart rate variability: standards of measurement, physiological interpretation, and clinical use. Circulation. 1996;93(5):1043–65.
40. Delaney JPA, Brodie DA. Effects of short-term psychological stress on the time and frequency domains of heart-rate variability. Percept Mot Skills. 2000;91(1994):515–24.
41. Billman GE. The LF/HF ratio does not accurately measure cardiac sympathovagal balance. Front Physiol. 2013;4:1–5.
42. Nater UM, La Marca R, Florin L, Moses A, Langhans W, Koller MM, et al. Stress-induced changes in human salivary alpha-amylase activity - associations with adrenergic activity. Psychoneuroendocrinology. 2006;31(1): 49–58.
43. Evans JD. Linear correlation. In: Straightforward statistics for the behavioral sciences. Pacific Grove: Thomson Brooks/Cole Publishing Company; 1996. p. 127–58.
44. Fleiss JL. The design and analysis of clinical experiments. New York: John Wiley & Sons; 1986.
45. Tabachnick BG, Fidell LS. Using multivariate statistics. 6th ed. New York: Harper and Row; 2013.
46. Cohen J. A power primer. Psychol Bull. 1992;112(1):155–9.
47. Collie A, McStephen M, Darby D, Maruff P, Makdissi M, McCrory P. CogSport: reliability and correlation with conventional cognitive tests used in postconcussion medical evaluations. Clin J Sport Med. 2003;13(1):28–32.
48. Bioglio SP, Ferrara MS, Macciocchi SN, Baumgartner TA, Elliott R. Test-retest reliability of computerized concussion assessment programs. J Athl Train. 2007;42(4):509–14.
49. Resch J, Driscoll A, Mccaffrey N, Brown C, Ferrara MS, Macciocchi S, et al. ImPact test-retest reliability: reliably unreliable? J Athl Train. 2013;48(4):506–11.
50. Mani R, Asper L, Khoo SK. Deficits in saccades and smooth-pursuit eye movements in adults with traumatic brain injury: a systematic review and meta-analysis. Brain Inj. 2018;32(11):1315–36.
51. Ventura RE, Balcer LJ, Galetta SL, Rucker JC. Ocular motor assessment in concussion: current status and future directions. J Neurol Sci. 2016;361:79–86.
52. Parsons TD. Virtual reality for enhanced ecological validity and experimental control in the clinical, affective and social neurosciences. Front Hum Neurosci. 2015;9(December):1–19.
53. Munafò M, Diedrick M, Stoffregen TA. The virtual reality head-mounted display ocular rift induces motion sickness and is sexist in its effects. Exp Brain Res. 2017;235(3):889–901.

Publisher’s Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.