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Reliability of Computerized Eye-Tracking Reaction Time Tests in Non-Athletes, Athletes, and Individuals with Traumatic Brain Injury

Belinda Lange, PhD, Flinders University, South Australia, Australia
Melissa Hunfalvay, PhD, Bethesda, Maryland
Nicholas Murray, PhD, East Carolina University, Greenville, North Carolina
Claire-Marie Roberts,* PhD, University of the West of England, Bristol, UK
Takumi Bolte, MSc, Clemson University, Clemson, South Carolina

ABSTRACT

Background: Eye tracking technologies and methodologies have advanced significantly in recent years. Specifically, the use of eye tracking to measure oculomotor and psychophysiological constructs quantitatively is gaining momentum. Reaction time has been measured in a number of different ways, from a simple response to a stimulus to more challenging choice or discrimination responses to stimuli. Traditionally, reaction time is measured from the beginning of a stimulus event to a response event and includes both visual and motor response times. Eye tracking technology can provide a more discrete measurement of reaction time to include visual components such as visual latencies and visual speed and can identify whether the person was looking at the target area when a stimulus was presented. The aim of this paper was to examine the reliability of the simple reaction time, choice reaction time, and discriminate reaction time tests measured using eye tracking technology. Additionally, we sought to establish performance norms and examine gender differences in reaction time in the general population. A final objective was to conduct a preliminary comparison of reaction time measures across different populations, including non-athletes, athletes, and individuals who had sustained a traumatic brain injury.

Methods: A sample of 125 participants was recruited to undertake test-retest reliability, analysed using Cronbach's alpha and intraclass correlation coefficients. A different data set of 1893 individuals, including athletes (n = 635), non-athletes (n = 627), and people with traumatic brain injury (n = 631) was compared using MANOVA to explore group differences in reaction time.

Results: Results demonstrated that overall, the tests had good test-retest reliability. No significant differences were found for gender. Significant differences were found between groups, with athletes performing best overall. Reaction times of people with traumatic brain injury were overall much more variable, showing very large standard deviations, than those of the non-athletes and athletes.

Conclusions: Future research should consider the accuracy of eye movements and various demographic variables within groups.

Keywords: athletes, choice reaction time, concussion, discriminate reaction time, eye tracking, simple reaction time, traumatic brain injury (TBI), vision

Background

Eye tracking has been employed across a broad number of disciplines to identify potential motor and cognitive issues and to evaluate and improve performance.[1-5] Eye tracking can be used to gain an understanding of neurological function, to identify neurological disorders, and to assess and evaluate performance during driving, sporting, and military activities.[3,4,6] The ability to attend to, to identify, and to react to various stimuli within our ever-changing surroundings is important for taking part in a broad range of activities involved in daily living and in demonstrating skill in sporting, driving, or military tasks. Reaction time (RT) is the elapsed time between the presentation of a sensory stimulus (visual, auditory, or tactile) and the subsequent behavioural response.[7] The required response to the stimulus can be a single response to a single stimulus (simple reaction time; SRT), such as the press of a button when a light goes on or the response of an athlete starting to run when a starting gun sounds. Alternatively, choice reaction time (CRT) is the response to more than one stimulus when each stimulus requires a different response. CRT involves the recognition and interpretation of the stimulus before the response is initiated. Discriminate reaction time (DRT) requires a response to only one stimulus when several different stimuli are presented, such as responding only to the

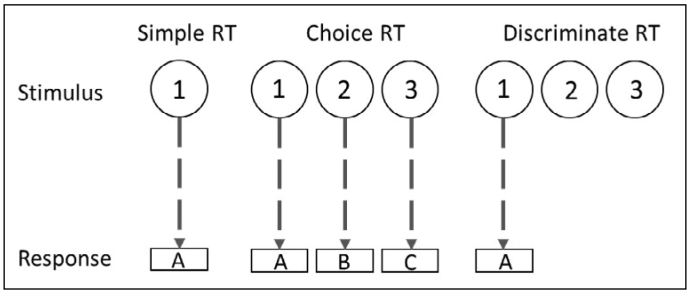

Figure 1. *Diagrammatic representation of simple reaction time, choice reaction time, and discriminate reaction time (adapted from Magill, 2001)*

colour green and ignoring all other colours that are presented (Figure 1).

Reaction time can be used to evaluate the performance of a motor skill and can provide information about how a person senses and interacts within their environment and how they attend to a specific task. Simple reaction time assesses a person's ability to respond automatically to a stimulus and depends on intact sensory and motor pathways.[8] Choice reaction time (CRT) assesses a person's ability to identify a stimulus and to decide on an appropriate response. Discriminate reaction time (DRT) assesses a person's ability to respond to specific stimuli and to ignore other stimuli.

RT is a measure of attention;[8] however, measurement can be separated into perceptual and motor components (Figure 2). In RT tasks that use visual stimuli, saccadic latency (elapsed time between when a peripheral stimulus appears and when the eye moves from the central target), visual reaction speed (time between the start of a stimulus and when the participant's eyes hit the target), and processing speed (time between when a participant's eyes hit the target and the response) are often considered together. These components are not measured in traditional methods of measuring RT, but this level of detail can provide valuable information to assist in parsing out the cognitive, attention, and motor components of the task. Physical ability has an impact on RT when the response requires the participant to perform a motor component, such as pressing a button or touching a specific location on a screen or table. Simple reaction time is an automatic response; however, CRT and DRT require that the participant identify the stimulus, make a choice about the response required, and perform the motor response. Issues in measuring RT include determining whether the participant was looking at the target area and consistency in the required response across tests. Eye tracking technology can capture this additional detail and provide a wealth of information that would not otherwise be captured in standard RT tests.

RT has been used in the assessment and training of sporting performance, driving research, neuropsychological testing, and in the exploration of differences in brain function across medical conditions such as concussion, brain injury, multiple sclerosis, dementia, schizophrenia and autism.[9-14] It can be affected by age, gender, handedness, central or peripheral vision, practice, fatigue, fasting, breathing cycle, personality type, exercise, and intelligence[7,15] and has been demonstrated to worsen in older adulthood, likely because of changes in the central nervous system.[10] Historically, males possess faster RT compared to females, due to differences in motor response as opposed to differences in muscle contraction.[10,16-18] However, this difference has reduced over time with the inclusion of more females in physical and sporting activities.[15] An increase in exercise and physical activity has been demonstrated to support faster RTs than are seen in individuals with sedentary lifestyles.[15] It has also been documented that athletes in sports such as basketball and baseball have faster RTs than non-athletes and people with sedentary lifestyles.[19-21] Again, this is likely to be the result of improved attention, increased blood flow, and faster central nervous system processing rather than changes in muscle strength and agility.[22] Furthermore, RT has been used as a discriminator between expertise levels in athletes.[23-28] Just as improved attention, increased blood flow, and faster central nervous system processing is thought to result in faster RTs,[8] impairments in any of these areas because of trauma or disease are likely to reduce RTs. For instance, choice reaction time has been shown to be slower in people with brain injury due to changes to the motor pathways.[8]

The literature exploring the use of eye tracking to measure RT has broadly focused on measurement of RT in different

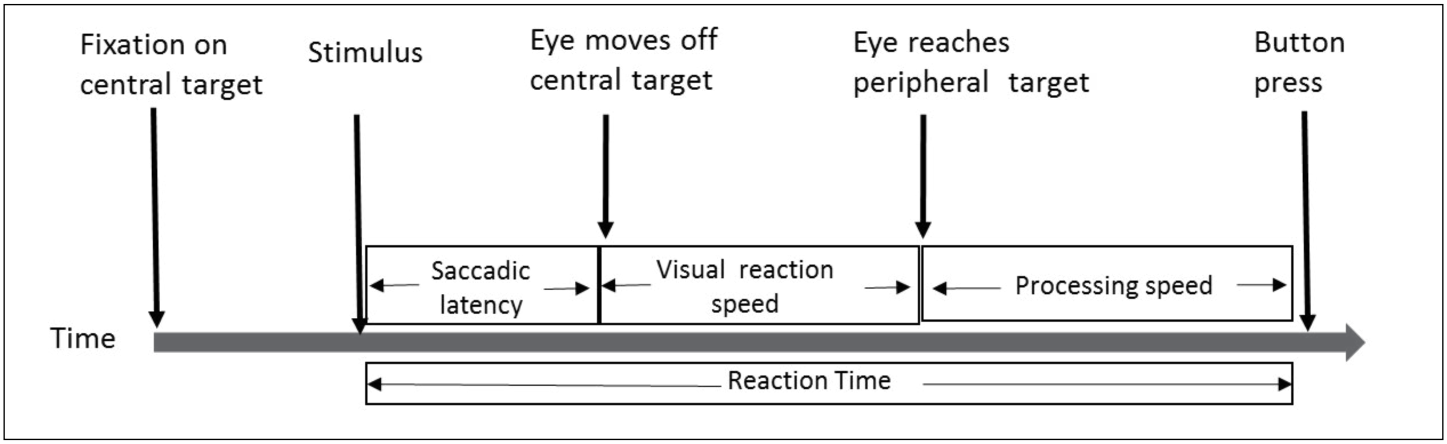

Figure 2. *Breakdown of events and time intervals related to the measurement of reaction time (adapted from Magill, 2001)*

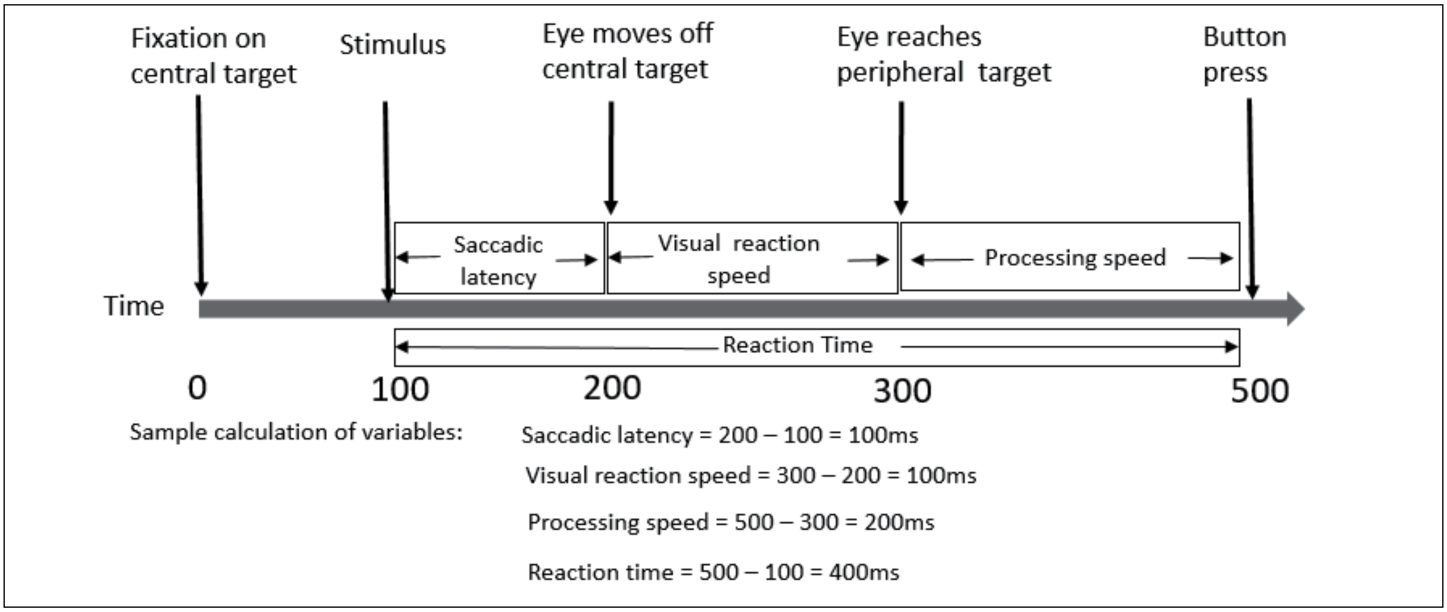

Figure 3. *Simplified breakdown of events and time intervals related to the measurement of reaction time*

healthy and impaired populations; however, there is limited published data on the reliability and norms associated with tests of SRT, CRT, and DRT using eye tracking. Standardised, reliable RT tests must be used to ensure that the test appropriately evaluates healthy, high-functioning and/or impaired individuals as a one-off tool, as well as to be able to compare changes in RT over time. A suite of eye tracking RT tests that include SRT, CRT, and DRT tasks have been developed based on frameworks outlined by Magill[29] and other motor learning and motor control scientists.[30] The feedback provided using the data collected from these tests includes saccadic latency, visual reaction speed, visual information processing, and (motor) RT. One important distinction between the framework outlined by Magill[29] and the suite of eye tracking tests under investigation is the term RT. Eye tracking RT tests measure RT as the time between the presentation of a visual stimulus and the press of a button on a keyboard (Figure 3). Magill[29] refers to this measure as response time (reaction time + movement time).

The aim of this paper was to examine a computerised suite of eye tracking RT tests (SRT, CRT, DRT) in order to establish reliability. Additional objectives included establishing performance norms and examining gender differences of the RT tests in participants from the general population. Finally, the study sought to explore differences in RT between different populations including non-athletes, athletes, and individuals who had sustained a traumatic brain injury.

Methods

Participants

Participants were selected for the reliability and normative data for this study through advertisements placed on the internet, social media, bulletin boards, and via word of mouth. Two different sets of data were used in this paper: 125 participants were recruited for the test-retest reliability and normative analysis, and 1893 participants were used for the analysis of group differences. This included athletes (n = 635), non-athletes (n = 627), and people with traumatic brain injuries (TBI; n = 631). To ensure an adequate sample size, a power analysis was conducted using Cronbach's alpha of >0.7, with alpha set at 0.05 and power set at 0.8. We chose power of 0.8 given that test-retest reliability requires a correlation coefficient of >0.65 as a minimum. Given the power analysis, a sample of 125 was deemed appropriate for the reliability analysis.

Reliability and normative analysis

A total of 125 participants between the ages of 18 and 40 years (Mean = 25.54, SD = 4.62), where 50 (40%) were female and 75 (60%) were male, were tested in the first phase of this study. Of the 125 participants, 68% were white, 17% black, 8% Hispanic, 1% Native American, and 6% opted not to report ethnicity. All participants passed pre-screening requirements. Exclusion criteria for normative data included participation in professional sport and abnormal neurological, psychiatric, or vision disorders. Neurological disorders included traumatic brain injuries and all movement-related disorders including Parkinsonism. Vision-related issues that prevented successful calibration of the eye tracking tests (such as extreme tropias, phorias, static visual acuity worse than 20/400, nystagmus, cataracts, or eyelash impediments) caused exclusion from the test. Additionally, participants who had consumed alcohol or drugs in the 24 hours before the test were excluded from the study. All participants provided informed consent to participate in this study in accordance with IRB procedure (IRB: UMCIRB 13-002660). Participants were compensated with a $20 gift card redeemable at a nationwide network of restaurants for their participation in the study.

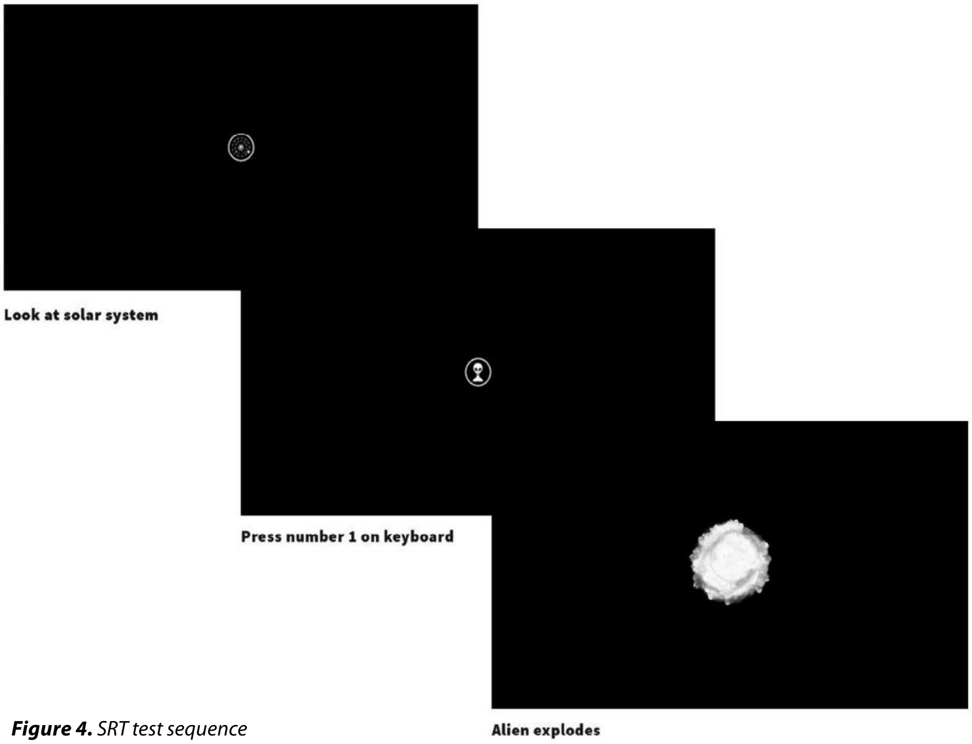

Figure 4. *SRT test sequence*

Differences in RT between non-athlete, athlete, and brain injury populations

For the group differences analysis, data from a total of 1893 participants was tested. The data from the athlete sample was selected by coaches and vision specialists within teams who had used the suite of eye tracking tests using RightEye technology (n = 635). Participants were professional athletes from baseball, American football, soccer, and golf. Participants with TBI (n = 631) were selected for the group analysis based on a diagnosis by a specialist (e.g. neurologist). Individuals in this group had a diagnosed traumatic brain injury and were between one and 180 days post-injury. As part of a clinical assessment, the participants were tested on suite of eye tracking tests using RightEye technology. Data from the non-athlete participants (n = 627) was selected for the group analysis if they did not have a TBI and were not professional athletes.

Materials and Equipment

All data was obtained using the same materials and equipment. The participants were seated in a stationary (non-wheeled) chair that could not be adjusted in height at a desk within a quiet, dimly lit private testing room in a commercial office or local library. The participants were asked to look at a NVIDIA 24-inch 3D Vision monitor that could be adjusted in height and which was fitted with an SMI 12” 120 Hz remote eye tracker connected to an Alienware gaming system and a Logitech (model Y-R0017) wireless keyboard and mouse. Each participant’s head was unconstrained during the testing.

Testing Procedure

After providing written informed consent, participants were asked to complete a pre-screening questionnaire and an acuity vision screening test, where they were required to identify four shapes presented on the screen; each shape measured 4 mm in diameter. The 4 mm shape diameter equated to a visual acuity of 20/62, which was deemed adequate for testing as no smaller stimulus was presented during the suite of tests. This ruled out the possibility that results could be impacted by poor visual acuity. If any of the pre-screening questions were answered positively or any of the vision screening shapes were not correctly identified via a verbal response, then the participant was excluded from the reliability and norming portion of the study. Participants were then asked to sit in front of the eye tracking system at an exact distance of 60 cm (ideal positioning within the head box range of the eye tracker) from the eye tracker for standardization before testing. A nine-point calibration test was conducted with points spanning the computer screen. Participants needed to pass all nine points to proceed with testing. Upon successful calibration, the SRT, CRT, and DRT tests commenced. Written instructions and animations were provided before each test to model appropriate behavior. The tests commenced immediately after one another.

Simple Reaction Time (SRT). In the SRT test, the participant viewed one stimulus and only gave one response (Figure 4). In this test, the individual looked at a 3 cm target (solar system) located in the center of the screen. When their eyes were confirmed to be looking within the target, the center target changed shape randomly. When the participant

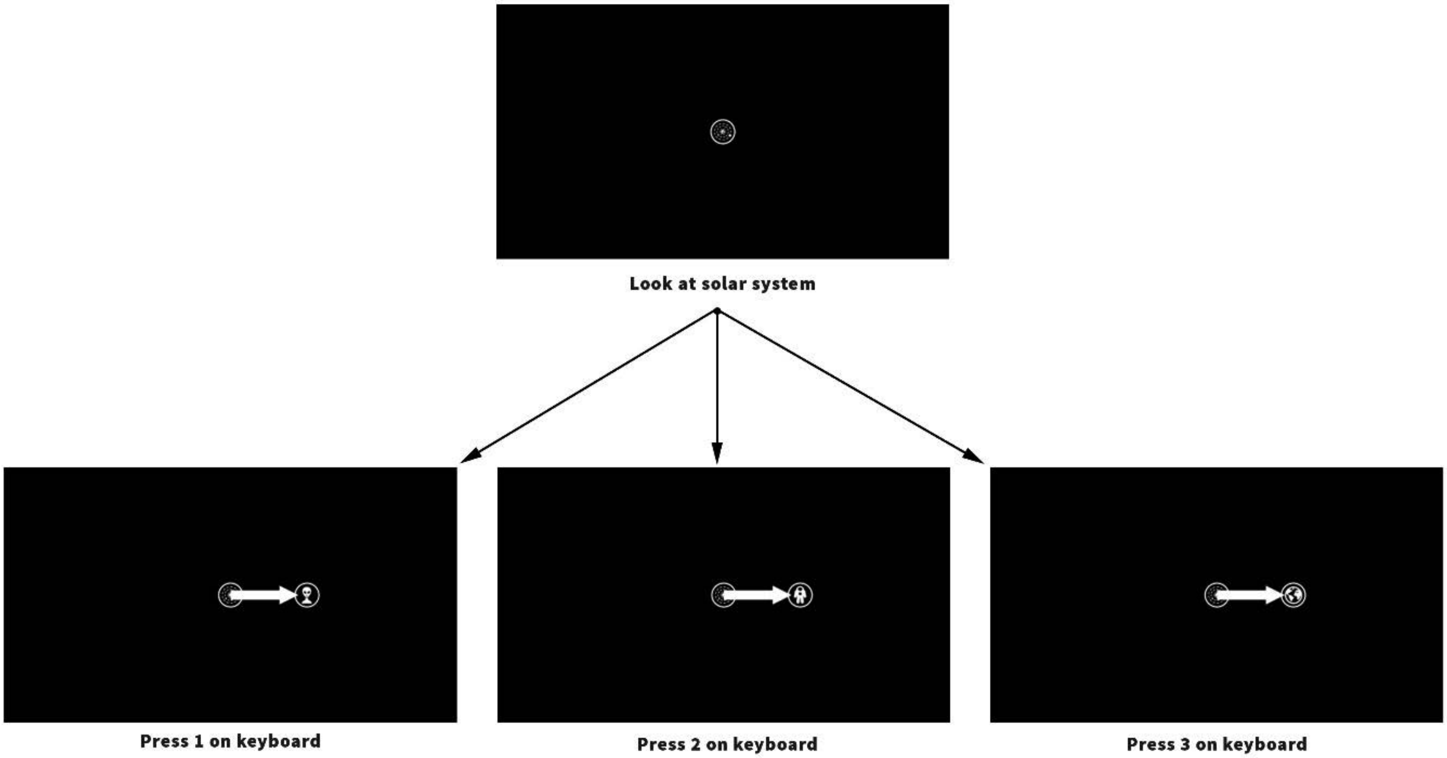

Figure 5. *CRT test sequence. Stimuli can appear at one of four locations (north, south, east, and west).*

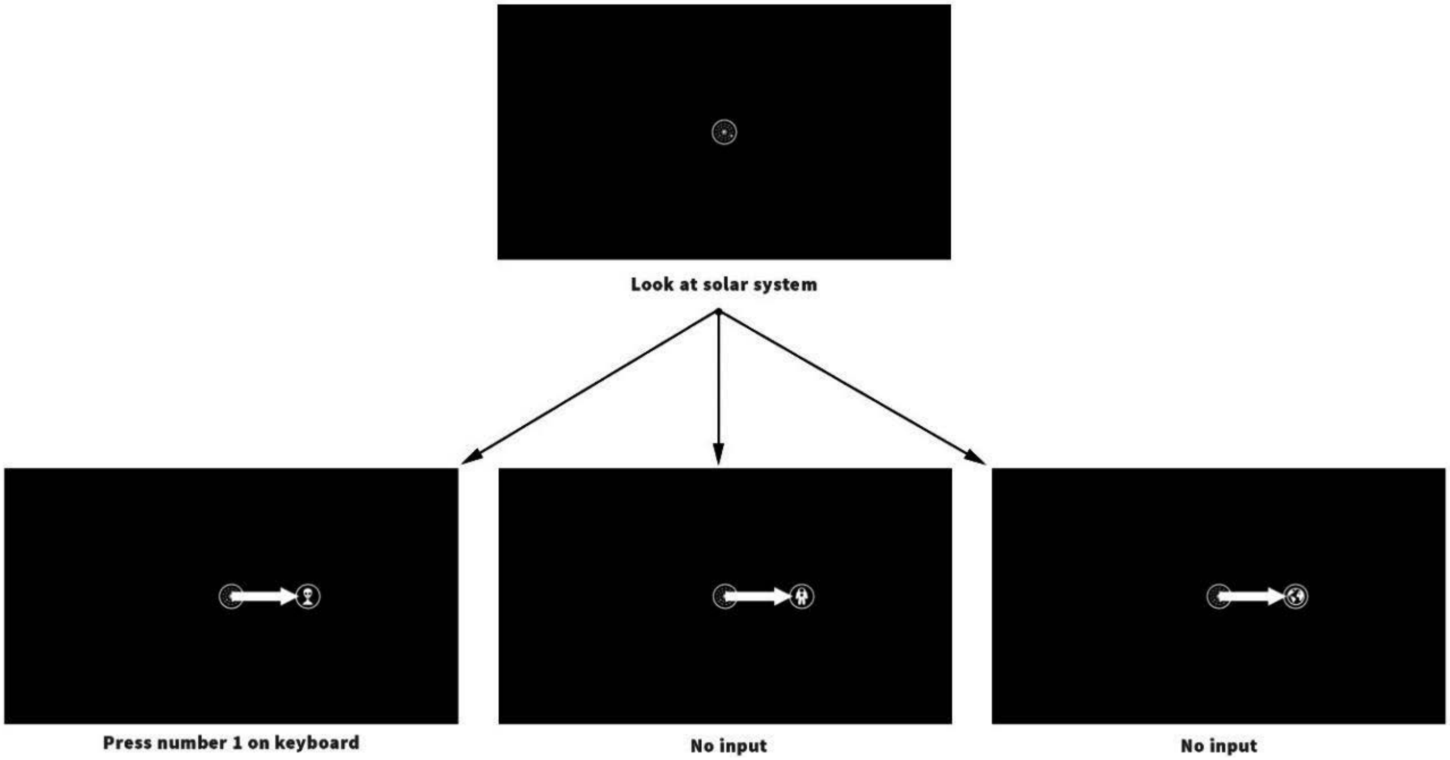

Figure 6. *DRT test sequence. Stimuli can appear at one of four locations (north, south, east, and west).*

detected that the target had changed (to an alien symbol), they were asked to press the number 1 on the keyboard. Reaction time was measured in milliseconds. Results were reported as an average across eight trials. Two practice trials were given before the eight test trials. The SRT testing took approximately four minutes to complete.

Choice Reaction Time (CRT). In the CRT test, the participant viewed three stimuli and was asked to provide one of three responses (Figure 5). In this test, the individual looked at a center target (solar system). When their eyes were confirmed to be looking within the target, an arrow moved out from the center in one of four directions (up, down, left, or right) for 8 cm. A stimulus was presented at the end of the arrow once the final location was reached. There were three stimulus choices, each requiring a different response. There was one response per stimulus (e.g., number 1 button, number 2 button). Time to respond was measured in milliseconds and reported as an average across eight trials. Four practice trials were given before the eight test trials. If the practice trials were not completed adequately, the protocol required instructions to be re-read. None of the participants failed to complete the practice trials, therefore testing proceeded. The CRT testing took approximately five minutes to complete. Four metrics were calculated for CRT and averaged across trials. Saccadic latency was calculated as the time between the presentation of the arrow from the center target to the time when the eye began to move. Visual reaction speed was calculated as the time between the presentation of the arrow from the center target to when the eye reached the stimulus. Processing speed was calculated as the time between when the eye reached the stimulus and the button was pressed. RT was calculated as an accumulation of both visual reaction speed and processing speed. Response accuracy was also calculated as the percentage of correct choices in responses.

Discriminate Reaction Time (DRT). In the DRT test, the participant viewed three stimuli and was required to respond to only one stimulus (Figure 6). In this test, the participant looked at a center target; when their eyes were confirmed to be looking within the target area, an arrow moved out from the center in one of four directions (up, down, left, or right) for 8 cm. At the end of the arrow, a stimulus was presented. There were three stimulus choices. Only one stimulus required a response from the participant, which was to press the number 1 button on the keyboard. Time to respond was measured in milliseconds and reported as an average across eight trials where the correct stimulus was presented. A total of 12 overall trials was shown to the participant. Four practice trials were given before the eight test trials. The DRT testing took approximately five minutes to complete. The same five metrics for CRT were also calculated for DRT and averaged across trials.

Validity by Design

Validity by design (face or priori validity) is concerned with whether the test seems to measure what it claims to measure. The suite of reaction time tests using RightEye technology have several validity by design elements built into the tests. These fall into two categories, test stimuli and test logic and flow. In addition, to ensure overall testing accuracy, each tester is trained on how to perform each test with accuracy and consistency. Each tester is given one hour of dedicated training, concluding with a test in the form of a demonstration to an experienced tester prior to administering the tests to any participants.

Test stimuli: Prior to the initiation of each test, a distance box is shown on the instruction screen that allows the tester to see the distance the participant is sitting from the screen. This metric is reported in real time. Distance from the screen is an important validity metric to the various visual outputs provided by the tests. This ensures that distance is compliant with requirements. All stimuli presented are the same size to ensure no conflict in results. The stimuli are always white, and the background of the screen is always black in these tests to ensure maximum contrast for people with possible color deficiencies.

Test logic and flow: For each RT test, the remote eye tracker can recognize the precise location of the participant's eyes. Using this information, stimuli are controlled to ensure accuracy in results. For example, the test does not show the next stimulus presentation (trial) if the eyes are not located within the center of the screen. When the eyes are within the center of the screen, the stimuli are presented, ensuring the same starting point for every trial. Stimuli are randomly presented in terms of time and location. The random nature prevents predictability of the test, thereby adding another layer of validity to the results. To ensure that there is no impact on the results due to possible confusion at the beginning of a test, there are always practice trials presented (2 for SRT and 4 for CRT and DRT). Finally, should a participant fail to respond to a minimum number of stimuli (<4) per test, then the results are flagged, and decisions can be made by the tester as to whether the test needs to be redone. All stimuli, test logic, and flow decisions enhance the suite of reaction time tests using RightEye technology, thereby providing further confidence in the accuracy of the results.

Data Analysis

Reliability and normative analysis

Reliability of the RT measures was evaluated using intraclass correlation coefficients (ICCs) between trials. In addition, test-retest reliability was evaluated with Cronbach's alpha (CA) and the standard error of measurement (SEM) for each ICC. Alpha level was set at $p<0.05$ for all statistical tests. The ICC indicates the relative reliability and is interpreted using the following criteria: ICC > 0.75 specifies excellent reliability, and 0.40 < ICC < 0.74 represents fair to good reliability.[33]

Table 1. Descriptive Statistics for Test 1 and Test 2 and Trial-to-Trial Reliability

Test Type & Metric		Mean	Std. Dev	Std. Error	95% CI Lower	95% CI Upper	Min	Max	SEM	CA	ICC
Simple RT Test											
Reaction Time (ms)	T1 T2	442.74 444.90	67.02 76.32	6.01 6.85	430.83 431.44	454.65 458.46	315.06 341.80	806.70 992.13	7.87 8.23	0.87	0.75
Choice RT Test											
Saccadic latency (ms)	T1 T2	266.73 264.65	35.39 35.80	3.17 3.21	260.44 258.29	273.02 271.02	191.85 188.53	431.35 401.46	3.17 3.21	0.89	0.94
Visual Reaction Speed (ms)	T1 T2	143.63 142.51	19.06 19.29	1.71 1.73	140.23 139.08	147.01 145.93	103.30 101.51	232.26 216.17	1.71 1.73	0.94	0.89
Processing speed (ms)	T1 T2	427.15 423.81	73.90 75.51	6.63 6.78	414.01 410.38	440.29 437.23	217.35 161.32	688.09 692.30	7.56 7.20	0.89	0.94
Reaction Time (ms)	T1 T2	832.50 818.14	69.73 63.02	6.26 5.56	820.10 806.93	844.89 829.33	659.99 616.82	1094.34 1029.13	7.36 6.63	0.80	0.66
Response accuracy (%)	T1 T2	6.86 6.88	0.86 0.83	.007 .073	6.71 6.73	7.01 7.02	5.00 5.00	8.00 8.00	0.08 0.07	0.91	0.84
Discriminate RT Test											
Saccadic latency (ms)	T1 T2	241.46 235.97	31.06 31.64	2.78 2.84	235.93 230.35	246.98 241.6	164.57 180.81	367.03 359.04	2.78 2.84	0.56	0.41
Visual Reaction Speed (ms)	T1 T2	148.00 144.63	19.04 19.39	1.70 1.74	144.60 141.18	151.37 148.07	100.87 110.82	224.95 220.06	1.71 1.74	0.56	0.41
Processing speed (ms)	T1 T2	148.00 144.63	19.04 19.39	1.70 1.74	144.60 141.18	151.37 148.07	100.87 110.82	224.95 220.06	1.71 1.74	0.56	0.41
Reaction Time (ms)	T1 T2	678.94 659.60	122.08 79.03	10.92 7.09	657.23 645.55	700.63 673.65	509.89 484.86	1608.76 961.52	11.54 8.12	0.80	0.62
Response accuracy (%)	T1 T2	7.31 7.27	0.71 0.67	.063 .05	7.17 7.15	7.43 7.39	5.00 5.00	8.00 8.00	0.06 0.06	0.93	0.86

*p < 0.05; ms = milliseconds; RT = reaction time; T1 = test 1; T2 = Test 2; Min = Minimum; Max = maximum; CA = Cronbach's Alpha; ICC = Intraclass Correlation Coefficient; SEM = Standard errors of measurement

Differences in RT between non-athlete, athlete, and brain injury populations

To test the differences between groups, the following statistical analyses were applied: 1) Alpha was set at $p<0.05$ for all statistical tests; 2) For multivariate analyses of variance (MANOVA), significant main effects and interactions were evaluated through follow-up univariate analysis of variance (ANOVA) tests; 3) Tukey's HSD post-hoc analysis was used when necessary to evaluate significant main effects; and 4) When necessary, violations of the sphericity assumption were corrected using Greenhouse-Geisser adjustments of the degrees of freedom.

Results

The descriptive statistical output for each variable demonstrated that the data was normally distributed. In addition, skewness and kurtosis values were not significant for any of the variables. Irrespective of the trial size, the data met the assumption of normality. Furthermore, the data met the assumption of homogeneity of variance (i.e., variances will remain the same across groups) as Levene's test with each case resulted in p greater than 0.05. Because of these findings, there were no excessive RT trials, and as such, no collected data was excluded from the analysis.

Reliability and normative analysis

Normative data, Cronbach's alpha, intraclass correlation coefficients, and associated SEM for test reliability (Test 1 & Test 2) are reported in Table 1. Observations for several variables demonstrated strong reliability. Several Cronbach's alphas were above an acceptable level of 0.7, which is considered ideal.[31] Per George and Mallery's[32] criteria, nine of the 11 eye tracking variables demonstrated Acceptable (0.7) to Excellent (0.9) test-retest reliabilities. Only two eye tracking variables demonstrated Questionable (0.6) reliability, and no variables were found to have Unacceptable (<0.5) test-retest reliabilities.

Calculated SEMs for SRT and CRT: RT and DRT: processing speed and RT suggest that these measures represent an accurate assessment. All ICC were statistically significant at the $p<0.05$ level. The test-retest reliability and internal consistency does provide a clear indication these are in fact measuring variants of reaction time.

Using a multivariate analysis of variance (MANOVA), we compared gender for all dependent variables. This analysis revealed a non-significant finding (Wilks' Lambda = 0.927, F(9, 160) = 1.41, p = 0.188), so no further follow-up ANOVAs were conducted for this variable.

Differences in RT between non-athlete, athlete, and brain injury populations

A multivariate analysis of variance (MANOVA) was employed to examine the group differences (athletes, non-athletes, individuals with traumatic brain injury) on the all RT measures. This test revealed significant main effects for Group (Wilks' Lambda = 0.357, F(22, 1142) = 34.97, p < 0.001, Np2 = 0.403). Follow-up tests revealed ANOVAs significant difference between Groups for all of the variables except CRT: RT metric (Table 2). Tukey's post hoc test revealed that the

Table 2: Group differences on all RT tests

Dependent Variable	Athletes	General population	TBI	F-statistic	Sig.	Np2
Simple RT Test						
Reaction time (ms)	415.64 (43.40)	448.52 (82.24)	516.11 (175.14)	13.929	0.001	0.201
Choice RT Test						
Saccadic latency (ms)	251.47 (41.13)	266.32 (35.49)	220.58 (71.62)	44.07	0.001	0.124
Visual reaction speed (ms)	136.27 (24.17)	143.41 (19.11)	125.61 (62.10)	11.662	0.001	0.136
Processing speed (ms)	419.50 (79.68)	430.92 (83.03)	598.44 (220.34)	102.85	0.001	0.248
Reaction time (ms)	808.84 (58.81)	831.70 (79.15)	836.08 (371.61)	1.051	.363	0.003
Response accuracy (1-8)	7.22 (0.82)	6.87 (0.88)	7.17 (0.99)	10.402	0.001	0.132
Discriminate RT Test						
Saccadic latency (ms)	232.31 (29.31)	239.65 (32.66)	216.12 (56.15)	21.009	0.001	0.163
Visual reaction speed (ms)	142.38 (17.97)	146.88 (20.02)	126.69 (55.91)	20.944	0.001	0.142
Processing speed (ms)	240.83 (61.90)	283.08 (101.61)	372.18 (138.79)	49.57	0.001	0.237
Reaction time (ms)	615.53 (57.33)	674.18 (113.48)	715.00 (175.76)	21.758	0.001	0.065
Response accuracy (1-8)	7.87 (0.41)	7.28 (0.69)	7.67 (0.61)	63.804	0.001	0.170

ms = milliseconds; RT = reaction time

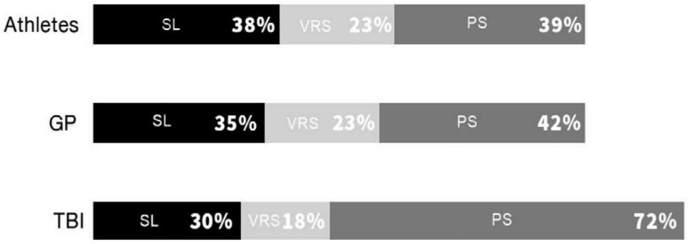

Figure 7. *CRT test proportional breakdown of events and time intervals related to the measurement of reaction time. SL = saccadic latency; VRS = visual reaction speed, PS = processing speed, GP = non-athlete, TBI = traumatic brain injury*

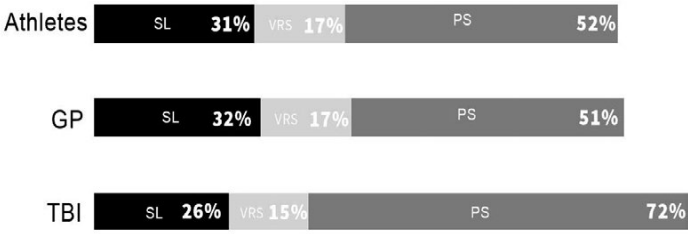

Figure 8. *DRT test proportional breakdown of events and time intervals related to the measurement of reaction time. SL = saccadic latency; VRS = visual reaction speed, PS = processing speed, GP = non-athlete, TBI = traumatic brain injury*

traumatic brain injury group differed from the athlete and non-athlete groups on the following tests and metrics: 1) SRT: RT; 2) CRT: visual reaction speed, processing speed, and response accuracy; and 3) DRT: RT. CRT: saccade latency, DRT: saccadic latency, processing speed, and response accuracy differed between all three groups. The athlete group differed from the traumatic brain injury and general population groups in DRT: response accuracy.

Discussion

This study examined a suite of RT tests using RightEye eye-tracking technology. Normative data was based on 125 participants from various ethnic backgrounds and both genders. This data is an adequate reference for comparison for individuals within the general population, who are not professional athletes and who do not have a TBI, between the ages of 11 and 65.[33] When comparing gender differences for this group, no significant differences were found. This finding aligns with more recent research describing the closing gap between gender differences in RT.[7,15] Historically, males have been reported to have faster RTs compared to females.[16,17] Changes in participation levels of females in sport and increases in physical activity levels are likely to have led to this reduced gender difference.[15]

The RT tests were also examined for test-retest reliability using Cronbach's alpha. Results demonstrate that overall, the suite of RT tests examined have good test-retest reliability and are reliable measures of RT. The SRT and CRT were found to have good to excellent reliability ($\propto \geq 0.80$), and the DRT was found to have acceptable to excellent ($\propto 0.56 - 0.93$) reliability. These results indicate confidence in the consistency of the RT tests over time. It is important to note that some of these metrics are novel due to the measurement ability of the eye tracker. For example, it is the first time that the measures of saccadic latency and visual speed have been tested for reliability, to the authors' knowledge.

The ICCs indicate the relative reliability of the tests. ICCs describe how strongly units in the same group resemble each other and are interpreted using the following criteria: An ICC > 0.75 specifies excellent reliability, and an ICC between 0.5 and 0.75 represents moderate to good reliability.[33] Taken together, the results revealed fair to excellent ICCs for all reaction time tests examined. Differences were found between non-athlete, athlete, and TBI groups with large sample sizes (non-athlete = 627, athlete = 635, TBI = 631). Significant main effects and significant differences between groups were found for all but CRT: RT. To display group differences effectively, the proportional time spent on each metric per group is shown in Figures 7 and 8.

For the SRT test, the TBI group differed from athletes and non-athlete groups and revealed slower SRT than the non-athletes and athletes. This is consistent with past research, where athletes have demonstrated faster RT responses than people in the general population.[19-21] Past research has also found that SRTs in people with traumatic brain injury have been shown to be significantly slower than people in the general population because of changes to the motor and cognitive pathways.[8]

For the SRT test, no significant differences were found between the athlete and non-athlete groups, although the means show differences in expected directions, with athletes being faster at 416 ms (SD = 43) and non-athletes at 449 ms (SD = 82). It is possible that results were not significantly different due to the lack of information regarding some of the demographics in the non-athlete group. Although the non-athlete group was screened for TBI, and participants reported not being athletes, other factors may have impacted results. For example, age or other related activities such as driving or amateur sport may have improved SRT in some participants in the non-athlete group, resulting in non-significant findings. This proposition is strengthened when reviewing the standard deviations, which are almost twice as high for the non-athlete group compared with the athletes, indicating that the non-athlete group was overall a more variable sample compared to athletes.

Interestingly, the standard deviations for all metrics across all RT tests were higher for the TBI group. The only exception was for the response accuracy in the DRT test. In some cases, the standard deviation was several hundred times higher (see Table 2 CRT: RT). The variability in this group could be interpreted as occurring because of the differences within the group based on time tested between injury (1-180 days) and a fundamental and sustainable outcome of having a TBI within the last six months. There is some evidence to suggest that RT remains more variable for many months after a diagnosed TBI. Ghajar and Ivry[34] demonstrated this by generation of saccades at earlier and more variable time points, as well as greater and more variable oculomotor error compared to those who were not neurologically impaired. In addition, Swick et al.[35] demonstrated increased variability in RT tests in military veterans with post-traumatic stress disorder, of which more than 75% (34 of 45) also had diagnosed TBI.

Significant differences were also found between groups in the CRT and DRT tests. Results show that the TBI group was significantly faster than the athletes, and athletes were significantly faster than non-athletes, in the saccadic latency metric. The TBI group was also significantly faster in visual speed for CRT, which is moving from the center target to the peripheral target. For DRT, the TBI group also trended towards faster visual reaction speed (M = 127) compared to the athletes (M = 142) and GP (M = 147). At first glance, this seems counter to expectations. However, when reviewing this in the context of the other variables, particularly processing speed, the results make sense. It seems that the TBI group moved sooner to the target but took significantly longer to process what was seen. This is consistent with past research showing that people with TBI can be impulsive and erratic.[36] Furthermore, Goswami and colleagues[37] found that former professional athletes with histories of TBIs showed the same results as the individuals with TBI group in this study rather than the athlete group. The athletes with TBI showed greater impulsive behavior, which was linked to hot spots at the orbitofrontal and temporal ends of the uncinate fasciculus via MRI testing.

Higher standard deviations found in this study would also support the finding that the traumatic brain injury group moved sooner but took much longer to process what was seen. This is consistent with Ghajar and Ivry,[34] who demonstrated that this population generated saccades at earlier and more variable time points. These results are also consistent with research undertaken by Dockree and colleagues,[38] who showed differences in people with TBI compared to non-TBI controls, with increases in variability in response time for the TBI group. Furthermore, this variability was not found in the SRT task, where cognitive load and related processing speed requirements were much lower. Intuitively, it could be expected that the athletes would be fastest in the saccadic latency and visual speed metrics, as athletes practice these skills more. Athletes were significantly faster than the non-athlete group, which is consistent with past research;[39,40] however, athletes were significantly slower than the TBI group, which would further suggest impulsivity from the TBI group. Future studies should consider the visual pathway taken to the target and accuracy of the eyes "hitting" the target in order to explore this issue in more granularity.

Past research has also found slower processing time for people with TBI as cognitive load increases.[41-43] Processing time is seen to exponentially increase in people with TBI compared to those without.[42] This study supports past research, especially when viewing the information processing responses for people with TBI in CRT compared to DRT. It is unclear, from past research, where the lower response time values come from specifically, as they have not been parsed out to include saccadic latency, visual speed, information processing, and RT. However, several papers discuss the lower cognitive processing demands in SRT and DRT tests that are postulated to result in lower DRT response time scores.[38,42,43] Results in the current study support this postulation across all three groups, where the athletes, non-athletes, and people with TBI all had faster information processing scores in the DRT test than the CRT test (CRT: 420, 431, 598; DRT: 241, 283, 372; respectively).

The TBI group was significantly slower in the RT metric for the DRT test (M = 715; SD = 176) compared to the non-athlete group (M = 674, SD = 113) and the athletes (M = 616, SD = 57). Significant differences were not found in RT between groups for CRT, although again results are in the expected direction (athletes: M = 809, SD = 59; GP: M = 832, SD = 79; TBI: M = 836, SD = 372). Such results are consistent with past research for both athletes and the TBI group.[19-21] Historically, athletes have responded with faster RTs compared to non-athletes.[20] People with TBI have also responded more slowly than non-impaired individuals.[11]

For the response accuracy metric, results revealed significant differences. For the CRT test, the TBI group differed from the athlete and non-athlete groups, where the athletes were more accurate and the non-athlete group was less accurate than the TBI group. The non-athlete group was also less accurate than the athletes and the TBI group in the DRT test. Athletes were also the most accurate on the DRT test. Well-documented research shows that there is often a trade-off between speed and accuracy in both the CRT and DRT tests.[44] When people are fast (speed), they often show lower accuracy. However, when they are slow, accuracy is increased. Results of this study show that athletes can be fast (RT metric) and accurate (response accuracy metric). The non-athlete group, however, showed more conflicted results between emphasizing speed over accuracy (CRT test) or accuracy over speed (DRT test). When comparing non-athletes to athletes, the athletes could manage speed and accuracy at high levels. This may be due to the practice they have been given, especially when RT requires a deadline.[45] Decisions in real-life scenarios rarely enjoy such temporal luxury for gathering evidence, but instead often need to be terminated before a pre-specified deadline, after which no reward can be earned (e.g., a quarterback throwing to a wide receiver). Furthermore, the stress induced by a faster response impacts RT,[44] and if athletes have more practice with an RT deadline, this may mitigate the speed-accuracy trade-off, allowing them to be both quick and accurate.

These results are also clinically useful in that the parsing out of the cognitive, attention, and motor components of the task can allow clinicians to target therapies specifically to areas that need attention. For example, patients who have experienced TBI may show deficiencies in processing but not RT. Therapy tailored to processing issues are very different from therapies used to improve a motor response. Precisely targeting issues can potentially reduce therapy time, allowing a patient to see more immediate results.

In summary, athletes showed faster RTs, spent less time processing what they saw, and were most accurate in their responses. Athletes were also more like one another across all metrics, with lower standard deviations. The TBI group was fastest in getting off the mark to the target (saccadic latency and visual speed) but then took several hundred milliseconds longer to process what was seen and to react (RT). The TBI group was more accurate than the non-athlete group (but took significantly longer to respond) and were less accurate than the athlete group. The non-athlete group often fell between the TBI and athlete groups, by showing SRT, CRT, and DRT RT metrics that were slower than athletes and faster than the TBI group. The non-athlete group took longer to get started (saccadic latency and visual speed) than both the athletes and the TBI group. Response accuracy for the non-athlete group was slower than both groups, suggesting a possible speed-accuracy trade-off.

Future research should consider the accuracy of the eye movements on the peripheral target. Specifically, consideration should be given to eye teaming; that is, did both eyes hit the target? How accurately was the peripheral stimulus targeted by the eyes? A possible limitation of this research is the non-random presentation of SRT, CRT, and DRT tests to participants, possibly resulting in an order effect. Future research should also consider other demographic variables within these groups, such as age, gender, and ethnicity, as well as a further examination of differences between sports. Finally, the TBI group was considerably more variable than the other groups; this may have been caused by the variation in post-injury dates and the severity of the TBI. Future research should narrow these dates and classify the severity of the TBI. Consideration should be given to examining differences within the TBI group to include different injury classification and time ranges since injury; for example, severe TBI, within one week of injury versus severe TBI, within 30 days of injury.

Conclusions

The suite of reaction time tests using RightEye technology has been demonstrated to provide reliable measures of SRT, CRT, and DRT. Normative data is adequate, allowing future results and individual participants to be measured against norms. As expected, the tests demonstrated differences in RT between groups (athletes, non-athletes, and people with TBI). Whereby athletes were overall fastest in their RT and response accuracy, people with TBI were fastest in saccadic latency and visual speed but significantly slower in processing speed. This study reveals that although visual metrics are not often calculated in RT tests, they can provide valuable information in these populations. Future research should focus on accuracy of eye movements to the peripheral target.

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Correspondence regarding this article should be emailed to Claire-Marie Roberts, PhD, claire-marie.roberts@uwe.ac.uk. All statements are the author's personal opinions and may not reflect the opinions of the representative organizations, ACBO or OEPF, Optometry & Visual Performance, or any institution or organization with which the author may be affiliated. Permission to use reprints of this article must be obtained from the editor.

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