RESEARCH ARTICLE

Reliability and Validity of a 9-Point Ocular Alignment Test of Cardinal Gaze using Eye Tracking

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ABSTRACT

The purpose of this study is to determine the reliability of eye-tracking enabled 9-Point Motor Function Test and to determine the validity of the eye-tracking system compared with a traditional Cover Test (CT). Fifty participants between the ages of 19-61 years were tested by a veteran Board-Certified Optometrist using the RightEye 9-Point Motor Function Test (MFT; eye tracking test) and a Cover Test. Participants completed both the 9-Point MFT and the Cover Test in random order and completed the 9-Point MFT test twice to assess test-retest reliability. Reliability was evaluated using Cronbach's Alpha (CA). Overall reliability was acceptable to excellent per statistical standards. CA were above an acceptable level of .7. Interpupillary distance and pupil diameter were >.9 which is considered excellent. CT and eye tracker displacement were found to be significantly related via Chi Square analysis (P< .001). Logistic regression showed accuracy for left eye as 79.1% and right eye 86.3%. ROC curves were significant (P< .001) for left and right eye displacement. AUC was very high at .879 and .903 respectively. The 9-Point MFT and resulting metrics were deemed to pass reliability and validity statistical standards and as such may provide clinicians with consistent quantifiable information on positions of gaze.

Correspondence regarding this article should be emailed to Nicholas P. Murray, PhD, at **murrayni@ecu.edu.** *All statements are the author's personal opinions and may not reflect the opinions of the College of Optometrists in Vision Development, Vision Development & Rehabilitation or any institution or organization to which the authors may be affiliated.* *VDR is indexed in the Directory of Open Access Journals. Online access is available at* **covd.org.**
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INTRODUCTION

A binocular vision disorder occurs when the eyes are misaligned or out of focus. Misalignment of the eyes is one of the most common eye problems.[1] Early work demonstrated approximately 32.2% of college students have binocular dysfunction with a substantial percentage (56%) being symptomatic; however, there is not a strong epidemiological study that truly demonstrates the prevalence in the United States.[1,2] Eye alignments are clinically categorized as orthophoric when normal, eso (phoric or tropic) or exo (phoric or tropic) when abnormal. Eye misalignments may occur in any direction (up, down, left, or right) and in one or both eyes. Conditions associated with misalignment of the eyes include convergence abnormalities and vertical heterophoria. The prevalence of persons with convergence insufficiency is estimated between 4.2 to 17.6% in children and 3.4 to 7.7% in adults.[3]

Binocular vision disorder also includes deficits in visual motor control, especially in tasks requiring eye movements.[4] This may result in reading discomfort, losing one's place on a page or difficulty copying items from one page to another. Symptoms associated with binocular vision disorder are

numerous and varied.[5] Common symptoms include headache, blurry vision, visual fatigue and tearing eyes. Binocular vision is also essential for the ability to perceive depth and relationships between objects, such as seeing which object is closer than another. Secondary symptoms may include fatigue, inability to concentrate, irritability, short attention span, burning of the eyes, motion sickness, vertigo and a general poor performance on tasks.[6]

When the eyes are not working well together in a person with binocular vision disorder, then there are also compensatory physical behaviors that occur.[5] These include head tilts, face pain, and pain in the upper back, shoulders, and neck. Standard practice for binocular vision disorder testing includes a sensorimotor examination.[7] The test consists of, in part, a check for the alignment of the eyes to determine if the extraocular muscles move together in nine fields of gaze.

Traditionally, testing the nine cardinal gaze positions is conducted manually using an H-pattern test, Hirschberg test, or similar clinical observational test. In pediatric patients, the typical notation of fix and follow is generally used to describe both visual acuity and gross motility.[7] Cover tests are also a standard approach for determining ocular deviations.[8] The challenge with observational testing includes the lack of sensitivity of results. For example, doctors often report a test of oculomotor movement with a result of either normal or within limits or abnormal. The outcome is largely dependent on the doctor's experience and skill. Greater depth of information such as a prism diopter measure of deviation, can be conducted with further testing using prisms during a Cover Test. However, this process is time-consuming and requires specific optometric expertise.[5]

Eye tracking is a tool that can track eye movements in the 9-positions of gaze. An eye tracker can provide quantitative measurements in the distance translated to prism diopters to provide doctors with highly specific results. Therefore, eye tracking may provide an additional or alternative to traditional testing. Hence, the purpose of this paper is twofold: to examine the use of an eye-tracking system to determine the reliability of positions of gaze in all nine cardinal points and, second, to assess the validity of the eye-tracking system compared with a traditional Cover Test.

METHODS

Participants

Participants were recruited through an optometry practice in Las Vegas, Nevada. A total of 50 participants were tested between the ages of 19-61 years (M = 34.48, SD = 11.86), 39 (78%, see Figure 1) were female and 11 (22%) were male. Of the 50 participants, 45% were white, 16% black, 28% Hispanic, 0% Native American and 11% opted not to report ethnicity. Participants had no prior experience with eye-tracking technology. This research was reviewed by an independent ethical review board and conformed with the principles and applicable guidelines for protecting human subjects in biomedical research.

Testing

A Board-Certified (the American Board of Optometry) optometrist with 31 years of clinical practice conducted the testing. Before data collection, the clinician was trained on using the RightEye vision system and became a certified RightEye provider.

Materials and Equipment

Eye Tracking Test

Stimuli were presented using the RightEye 9-Point Motor Function Test (MFT) on a Tobii I15 vision 15" monitor fitted with a Tobii 90 Hz remote eye tracker and a Logitech (model Y-R0017) wireless keyboard and mouse. The accuracy of the Tobii eye tracker was 0.4-degrees within the desired headbox of 32 cm x 21 cm at 56cm from the screen. The reliability of the RightEye system is well established in previous work.[15] The 9-Point Motor Function Test is an oculomotor test that consists of nine points of gaze, each presented one at a time for 2 seconds (see example gaze location sequence in Figure 1). The test takes 18 seconds to complete and varied between trials.

The 9-Point Motor Function Test records eye movements and distances of fixations from 9 opto-

types located throughout the screen. Optotypes are in the 9 positions of cardinal gaze to measure the six muscles of the eye as they move around the three axes of the eye. The eyes were considered fixated once the participants maintained a steady eye movement for 100 ms or longer.

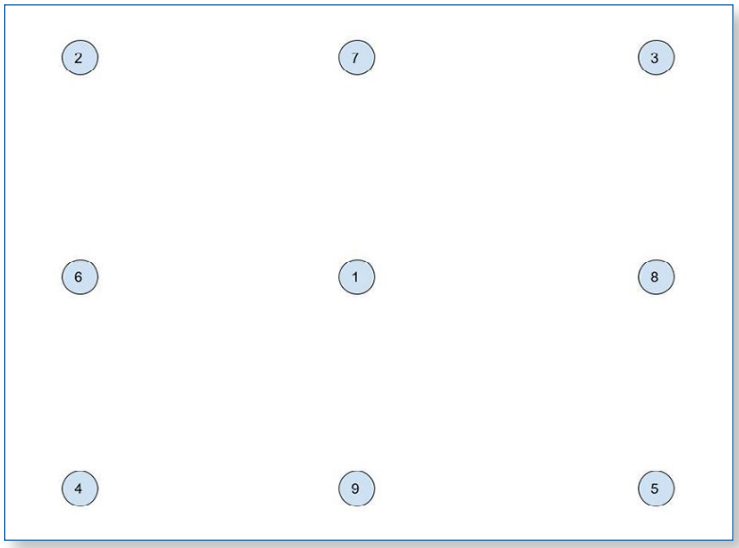


Figure 1. 9-Point Motor Test. Locations in Sequence of Appearance.

Various oculomotor calculations are derived from the 9-Point Motor Function Test. Calculations (metrics) for the 9-Point Motor Function Test include:

1. Distance between the eyes, measured in millimeters, also referred to as *interpupillary distance*, is measured from the center of the left and right pupils.
2. *Pupil diameter* is the average, standard deviation, and range of the pupil size, measured in millimeters.
3. *Disparity* is a measure of the distance between the left eye gaze point and the right eye gaze point at each of the gaze locations and reported in prism diopters.
4. *Horizontal, displacement* for each eye (left and right), at each target point, reported in prism diopters.
5. *Vertical displacement* for each eye (left and right), at each target point, reported in prism diopters.

The formula for conversion of distance to prism diopters is: D = Value/60 whereby D = prism diopters, V = value such as horizontal displacement, in centimeters to two decimal places; and 60 represents focal distance of 60 centimeters.

Cover Test

The examiner based their measurement on observed eye movements without responses from the participants. The examiner used a prism bar, a Bernell/Vision Training Eye black occluder, a ruler with a fixation target, and a phoropter with stand. A in color, was used to cover the eye during the Cover Test. The fixation target was the Accommodative Single Letter Target (such as an 'E'). Examiners instructed the participants to look at target and to "keep the target clear."

Procedure

All participants provided informed consent to participate in this study in accordance with IRB procedure (IRB: UMCIRB 13-002660). The study was conducted in accordance with the tenets of the Declaration of Helsinki.

Selection criteria included participants aged between 18 to 65 years with static visual acuity better than 20/400.[10] Participants were excluded from participation in the study if they had eye lash impediments or had consumed drugs or alcohol within 24 hours of testing.[11] Participants were excluded if they tested positive for strabismus. Upon arrival at the clinical center, the nature of the study was explained to the participants, and all participants provided written consent to participate. Following informed consent, participants were randomly selected to complete the optometric tester or the eye-tracking testing first, and then after finishing the first test the participant completed the other test.

At the eye tracking station, participants were asked to remove eyeglasses or contact lenses and were seated in a stationary (nonwheeled) chair that could not be adjusted in height. They sat in front of a desk in a quiet, private room. Participants' heads were unconstrained. Participants were positioned between 56-60cm (ideal positioning within the head box range) from the eye tracker. They were then asked to "follow the dots on the screen" to complete the 9-Point Motor Function Test. Once

complete the testing process was repeated a second time for test-retest reliability.

At the optometric testing station, to conduct the Cover Test, the participant was seated in a comfortable chair within the optometrist's clinical practice room and did not remove eyeglasses or contact lenses. The testing process was conducted in accordance with American Optometric Association: Clinical Guidelines and the Clinical Procedures in Primary Eye Care.[8] All subjects' heads were aligned vertically for testing to eliminate the impact of compensatory head tilts or turns. No prisms were used. The clinician first covered the left eye to test the right eye. The patient was asked to fixate on an object at 60 centimeters in the central point of gaze. The clinician then instructed the patient: "I would like you to look at this letter (examiner held up the Accommodative Single Letter Target, that is the fixation target). Keep watching the letter while I cover your eye."

Alternating Cover Test was used to determine tonic position by observing the eye as the occluder was removed from the test eye and placed in front of the fellow eye. Observation of the ocular movement(s) seen to pick up fixation as the stimuli was revealed indicated that eye's position of rest. If both eyes picked up fixation as its fellow was covered, binocularity was established. The movement toward fixation indicated the opposite direction of the subject's tonic posture. For example, if the eye moves nasally to pick up fixation, the tonic posture of that eye is exophoric. If the eye moved temporally to pick up fixation, the tonic posture of that eye was marked as esophoric. If no movement occurred upon the removal of the occluder, the tonic posture of that eye was marked as orthophoric. The Cover Test was used to determine whether a heterophoric subject regained alignment after the removal of the occluder from the covered eye. Once the participant finished with either testing station (eye tracking or optometric) they then went to the non-tested station. Upon completion of testing, the participant was debriefed and released. No compensation was given for participation in the study.

Data Analysis

Data was analyzed using Statistical Packages for Social Sciences (SPSS; Version 28). Reliability was evaluated using Cronbach's Alpha. Cronbach's Alpha indicates the relative reliability and is interpreted using the following criteria Unacceptable (<.6), Acceptable (.7), Very good (.8), Excellent (.9).[12]

Data analysis for validity testing of ocular deviation included a Chi-Square Test of Independence that was used to determine if the results of the 9-Point Motor Function Test and the Cover Test were related, that is if there was an association between the two tests. Data analysis only occurred on parts of the two tests that match. To perform this test, the 9-Point Motor Function Test was dichotomously divided into 0 = orthophoric (normal), or 1 = not orthophoric (not normal). Any data point assigned as 1, or not normal, was above 0.5 degrees of visual angle. These are based on typical scoring and normal values of these test. Typically, the mean distance phoria under a viewing of a distance of 6 m or 20 ft, ranges from 0 to 1 prism dioptre (pd) exophoria is around 2 pd, while the mean near phoria, for a distance at 33 or 40 cm, is typically exophoric and ranges between 3 and 6 pd. This included the error rate of the eye tracker, which is 0.4 degrees plus one standard deviation (0.1) to account for movement of the eye beyond the rate of error.[13] The Cover Test data was also dichotomously categorized for the Chi Square analysis. In this case, 0 = orthophoric (normal) and 1 = not orthophoric. Any data point assigned as 1, or abnormal, was rated by the clinician eso (phoric or tropic) or exo (phoric or tropic).

Next, a logistic regression was used to determine the probability of a participant as being categorized as 0 = orthophoric (normal), or 1 = not orthophoric (not normal). The alpha level was set to P<.05 and Omega squared (ω2) was used to determine effect size. Interpretation of Omega squared was a small effect size = 0.01 - 0.06; a medium effect size = 0.06 - .14, and a large effect size = >0.14.[14]

Finally, receiver operating curves were used to determine the sensitivity and specificity of the results. More specifically, the area under the curve was used to determine the benefit of using the test. Significant area under the curve with 95% confidence intervals ($P<.05$) was used to indicate the ability of each variable to differentiate orthophoric from not orthophoric participants. The criteria for a satisfactorily accurate area under the curve was set to the standard of greater than or equal to 0.7.[15] Cut-off points for sensitivity, specificity, and positive and negative predictive value (PPV and NPV, respectively) for each significant area under the curve were calculated. Optimal cut off points were determined by visually assessing which score combines maximum sensitivity and specificity.

RESULTS

Reliability

For each of the eye tracking metrics, tables 1-6 present the means and standard deviations for trials 1 and 2, the Cronbach's Alpha, and the associated test-retest reliability decisions.

Table 1: Test-retest Reliability of 9-Point Motor Function Test Variables: Pupil Metrics

Variable	Trial 1 Mean	Trial 1 SD	Trial 2 Mean	Trial 2 SD	CA	Decision
Interpupillary Distance	63.32	1.70	63.47	1.50	0.941	excellent
Pupil Diameter	3.52	0.32	3.54	0.31	0.952	excellent

Table 2: Test-retest Reliability of 9-Point Motor Function Test Variables: Disparity

Variable	Trial 1 Mean	Trial 1 SD	Trial 2 Mean	Trial 2 SD	CA	Decision
Disparity: Midline Primary	0.97	0.59	1.06	0.66	0.772	acceptable
Disparity: Superior Left	1.97	1.46	2.22	1.59	0.869	good
Disparity: Superior Right	2.68	1.87	2.54	1.76	0.896	good
Disparity: Inferior Left	1.84	1.15	1.78	0.98	0.923	excellent
Disparity: Inferior Right	2.03	1.58	1.81	1.28	0.889	good
Disparity: Midline Left	1.94	1.04	1.79	0.98	0.905	excellent
Disparity: Superior Midline	1.02	0.72	1.02	0.83	0.715	acceptable
Disparity: Midline Right	2.00	1.33	2.06	1.44	0.857	good
Disparity: Inferior Midline	1.20	0.76	1.15	0.86	0.736	acceptable

Table 3: Test-retest Reliability of 9-Point Motor Function Test: Horizontal Displacement; Right Eye

Variable	Trial 1 Mean	Trial 1 SD	Trial 2 Mean	Trial 2 SD	CA	Decision
Midline primary	0.49	0.54	0.62	0.83	0.865	good
Superior Left	0.83	0.65	0.91	0.75	0.805	good
Superior Right	1.46	2.28	1.28	1.58	0.778	acceptable
Inferior Left	1.68	2.81	1.47	2.52	0.776	acceptable
Inferior Right	0.88	0.73	1.22	1.64	0.700	acceptable
Midline Left	1.05	1.25	0.99	1.10	0.914	excellent
Superior Midline	0.54	0.53	0.61	0.51	0.826	good
Midline Right	0.83	0.73	0.81	0.67	0.807	good
Inferior Midline	0.85	1.00	0.90	1.24	0.776	acceptable

R = right eye; Horizontal displacement values measured in Prism diopters.

Table 4: Test-retest Reliability of 9-Point Motor Function Test: Horizontal Displacement; Left Eye

Variable	Trial 1 Mean	Trial 1 SD	Trial 2 Mean	Trial 2 SD	CA	Decision
Midline primary	0.44	0.43	0.59	0.79	0.701	acceptable
Superior Left	0.84	0.89	0.83	0.88	0.863	good
Superior Right	1.12	1.40	1.07	1.46	0.960	excellent
Inferior Left	1.67	2.48	1.47	2.01	0.766	acceptable
Inferior Right	0.81	0.76	1.10	1.76	0.739	acceptable
Midline Left	1.00	1.08	1.01	1.01	0.883	good
Superior Midline	0.46	0.37	0.65	0.84	0.731	acceptable
Midline Right	0.64	0.58	0.72	0.70	0.894	good
Inferior Midline	0.87	1.18	0.83	1.11	0.826	good

Table 5: Test-retest Reliability of 9-Point Motor Function Test: Vertical Displacement; Right Eye

Variable	Trial 1 Mean	Trial 1 SD	Trial 2 Mean	Trial 2 SD	CA	Decision
Midline primary	0.72	0.68	1.15	1.97	0.759	acceptable
Superior Left	1.07	0.89	1.14	0.86	0.928	excellent
Superior Right	2.01	1.90	1.74	1.45	0.783	acceptable
Inferior Left	2.09	2.56	1.69	2.22	0.808	good
Inferior Right	1.03	1.18	1.40	1.86	0.753	acceptable
Midline Left	1.23	0.90	1.12	0.83	0.917	excellent
Superior Midline	0.65	0.51	0.69	0.71	0.740	acceptable
Midline Right	1.08	0.97	1.03	1.05	0.885	good
Inferior Midline	1.43	1.73	1.09	1.38	0.807	good

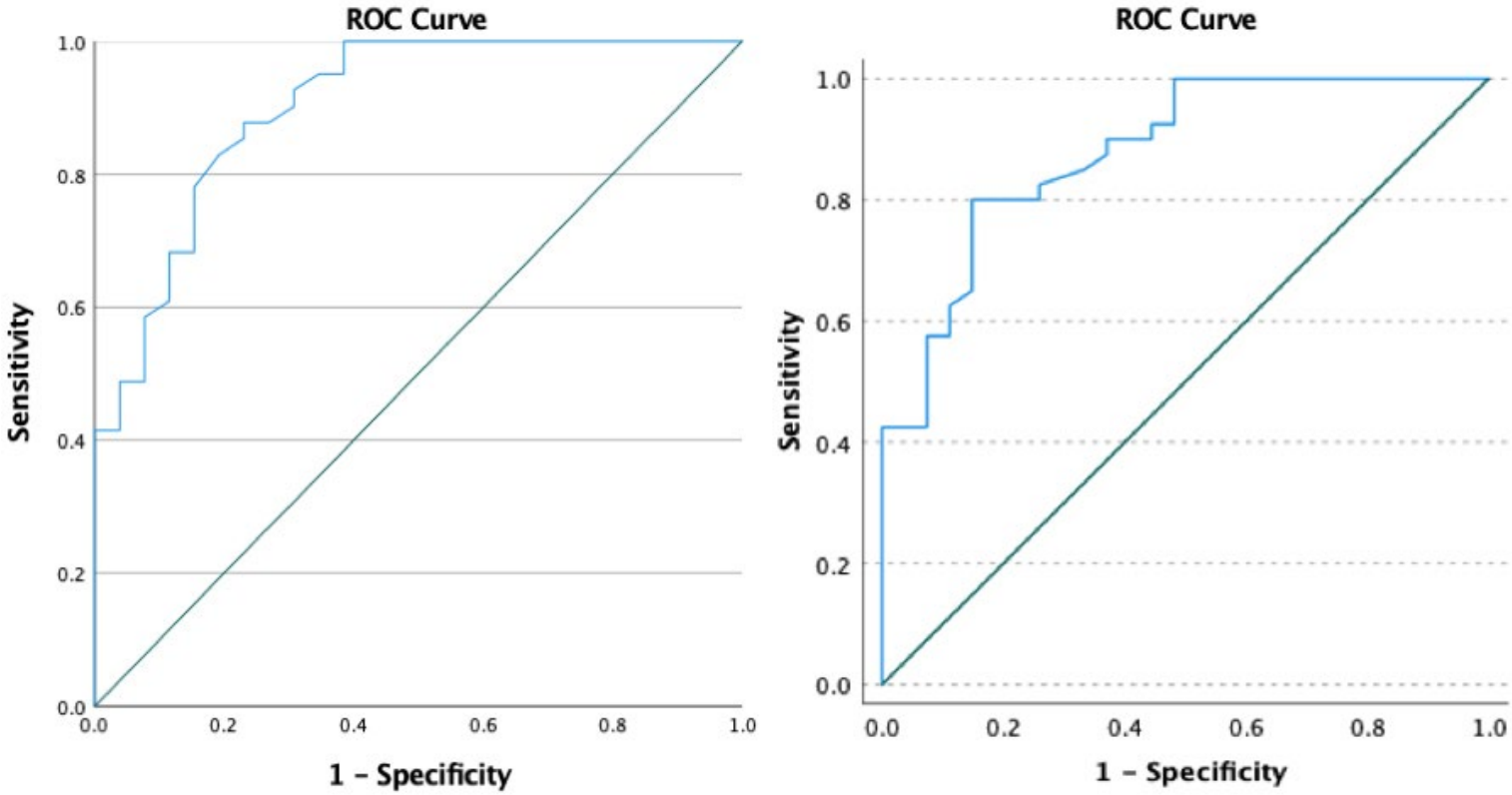
Table 6: Test-retest Reliability of 9-Point Motor Function Test: Vertical Displacement; Left Eye

Variable	Trial 1 Mean	Trial 1 SD	Trial 2 Mean	Trial 2 SD	CA	Decision
Midline primary	0.60	0.59	0.74	1.18	0.867	good
Superior Left	1.57	1.25	1.80	1.34	0.879	good
Superior Right	1.59	1.46	1.31	1.15	0.872	good
Inferior Left	1.61	2.35	1.19	1.56	0.805	good
Inferior Right	1.37	1.17	1.73	1.52	0.845	good
Midline Left	0.87	0.67	1.06	0.73	0.809	good
Superior Midline	1.38	1.19	1.17	0.88	0.813	good
Midline Right	1.01	0.80	1.11	0.77	0.885	good
Inferior Midline	1.60	2.03	1.14	1.44	0.853	good

Validity Results

Chi Square Analyses Results

For the *right eye,* Cover Test and eye tracker displacement were found to be significantly related, X2 (2, N = 67) = 30.660, P< .001. Cramér's V = .676 indicates the variables are highly related (V>0.5: strong association). The accuracy of the model is 83.58%. The proportion of values that scored 0 (orthophoric) from values of 0 (true negative) was 88.9%. The proportion of values that scored 1 (not orthophoric) from values of 1 (true positive) was 80%. For the *left eye,* Cover



Figures 2a & 2b. ROC curves with sensitivity and specificity values for the a) right eye and b) left eye.

Test and eye tracker displacement were found to be significantly related, Pearson X2 (2, N = 67) = 33.044, P < .001. Cramér's V = .702 indicates the variables are highly related (V>0.5: strong association). The accuracy of the model is 85.07%. The proportion of values that scored 0 (orthophoric) from values of 0 (true negative) was 88.9%. The proportion of values that scored 1 (not orthophoric) from values of 1 (true positive) was 82.5%.

Logistic Regression

The right eye Cover Test was significantly related to the eye tracker displacement value, $\chi 2$ = 37.362; P < .001, Nagelkerke *R*2 = 0.602. Accuracy of the model was 83.6%, sensitivity was 77.78% specificity was 87.50%, false positive is 19.23%; false negative is 22.22%. The PPV was 80.77%; the NPV was 85.37%. A moderate effect size $\omega 2$ = 6.43% was found for the right eye. The left eye Cover Test was significantly related to the eye tracker displacement value, $\chi 2$ = 34.827; *P* < .001, Nagelkerke *R*2 = 0.548. Accuracy of the model was 79.1%, sensitivity was 77.8% specificity was 80.0%, false positive is 27.59%; false negative is 22.22%. The PPV was 72.41%; the NPV was 84.21%. A moderate effect size $\omega 2$ = 6.50% was found for the left eye.

Receiver Operating Curves

Receiver operating curves were significant (*P*< .001) for right eye displacement. Area under the curve was very high at .903 and visually displayed in the receiver operating curve (Figure 2a). Receiver operating curves were significant (*P*< .001) for left eye displacement. Area under the curve was very high at .879 and visually in the receiver operating curve (Figure 2b).

DISCUSSION

The purpose of the study is to examine the use of the 9-Point Motor Function Test using eye tracking to determine the reliability of positions of gaze in all nine cardinal points. Overall, reliability was acceptable to excellent according to statistical standards. Cronbach's Alphas are above an acceptable level of .7. many were deemed 'good' (CA > .8).[12] Reliability for interpupillary distance and pupil diameter were found to be excellent (CA >.9). These results show that the 9-Point Motor

Function Test performed consistently for individuals from one attempt to the next in all nine cardinal points. Reliability is an important foundation for a clinical tool before further use, as a reliable tool determines that future results can be examined with confidence.

The 9-Point Motor Function Test was also examined for validity by comparing outcomes with a Cover Test. Results revealed an orthophoric alignment in the Cover Test was demonstrated equally in an 9-Point Motor Function Test. Similar finding was observed for non-orthophoric individuals. The accuracy of these findings for both left and right eyes was greater than 80% with very high area under the curve values. Clinical providers can expect Cover Test results and 9-Point Motor Function Test results to show consistent findings. Given the results, the 9-Point Motor Function test may provide an alternative to traditional testing with the added benefit of reliably quantifying distances in horizontal and vertical positions of gaze. One distinction between the tests and a potential limitation was the removal correction for the computerized test and not for Cover test. Further, the focus of this study was non-strabismus patients, as the alternate cover test will not differentiate between strabismus and phoria. Two strengths of our study are the choice of a within design in which participants were their controls and the use of a counterbalanced design; however, there is a potential for bias as the same optometrist performed both tests. This bias is reduced by the counterbalance design; however, future work should consider using two optometrists with blinded to the other test.

Future studies should compare prism diopter measurements with eye-tracking diopter measurements in each of the 9 points of cardinal gaze. In this way, the eye-tracking test can be examined for specific distance deviations compared with clinical gold standards. Given a potential high prevalence of binocular vision disorder and considering effective treatments are available, utilizing a quick, accurate, reliable, and quantitative measure of oculomotor movement deviation may assist clinicians with diagnosis of binocular vision disorders and in turn assist patients in reducing symptoms and improving patient care.[5,16]

In conclusion, eye tracking provides quantitative measures of eye movements. The 9-Point Motor Function Test examines the positions of cardinal gaze. Resulting metrics from this test were deemed to pass reliability and validity statistical standards and as such may provide clinicians with consistent quantifiable information on positions of gaze.

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