

# Synchronization of a Removable Optical Element with an Eye Tracker: Test Case for Heterophoria Measurement

Liat Gantz<sup>1</sup> and Avi Caspi<sup>2-4</sup>

<sup>1</sup> Department of Optometry and Vision Science, Hadassah Academic College, Jerusalem, Israel

<sup>2</sup> Department of Electrical and Electronics Engineering, Jerusalem College of Technology, Jerusalem, Israel

<sup>3</sup> Second Sight Medical Products, Inc., Sylmar, CA, USA

<sup>4</sup> Wilmer Eye Institute Johns Hopkins University, Baltimore, MD, USA

**Correspondence:** Liat Gantz, Department of Optometry and Vision Science, Hadassah Academic College, 37 Haneviim St., Jerusalem 91010, Israel. e-mail: [liatg@hac.ac.il](mailto:liatg@hac.ac.il)

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**Purpose:** Heterophoria describes the deviation of the optical axes in the absence of binocular fusion. Eye trackers (ET) can provide an objective assessment but are not broadly used clinically. We examined the feasibility of combining an infrared (IR) pass-filter, IR detector, and an off-the-shelf ET. The proposed setup was validated against the broadly used cover test (CT). Furthermore, the setup was used to examine whether testing conditions can affect the measurements.

**Methods:** An IR detector was attached to a handheld IR-pass filter that blocks visible light to provide occlusion while passing IR light for eye tracking. The detector senses the IR illumination of the eye tracker, creating a recordable signal of the occluder position synchronized with eye positions acquired by the SMI Red250 tracker. The mean of three measurements of each condition, three versus ten seconds occlusion, the occluded eye, and ET versus CT results were compared using the Wilcoxon test, correlation and Bland and Altman plots. Differences between measurements that were within 2<sup>Δ</sup> were considered clinically insignificant.

**Results:** Thirty normally-sighted subjects (mean age 24.50 ± 2.20, range 20–28) with heterophoria ranging between 14<sup>Δ</sup> exophoria and 4<sup>Δ</sup> esophoria were recruited. There was no significant difference between the occluded eyes. However, there was a difference between 3 and 10 seconds' cover duration. The CT data were more similar to the 10 seconds cover duration, although differences were less than the clinical resolution of 2<sup>Δ</sup>.

**Conclusions:** An inexpensive off-the-shelf ET can be used to measure heterophoria with controlled testing parameters.

**Translational Relevance:** Our study demonstrated a robust technique for synchronization of an optical element such as an IR cover, with an off-the-shelf commercial eye tracker. The synchronization of optical elements with eye tracking, which has been described here for heterophoria, can be adapted for other clinical measurements.

## Introduction

Heterophoria is a deviation of the ocular optical axes in the absence of binocular fusion.<sup>1-3</sup> The measurement of heterophoria represents the motor fusional demand posed on the visual system to obtain straight-ahead gaze.<sup>4</sup> This measurement is vital during binocular visual assessment to diagnose and correct binocular visual anomalies.<sup>5</sup> Nontreated signif-

icant heterophoria is associated with certain clinical symptoms, such as blurred vision,<sup>6</sup> headaches,<sup>7</sup> diplopia,<sup>8</sup> and binocular visual dysfunctions.<sup>9,10</sup> As such, the accuracy of heterophoria measurement is important for clinical evaluation and assessment.<sup>11</sup>

Heterophoria can be quantified with clinical tests that are based on dissociation of the two eyes by means of covering one eye or by displaying differing elements that cannot be fused by the two eyes.<sup>12</sup> In the cover test, a clinician can observe the corrective eye

movement after the removal of the cover. In dissociation tests<sup>13</sup> various optical elements are placed in front of the eyes to produce different visual views in each eye. The patient reports the location of the different visual views in one eye relative to the location in the fellow eye. For example, using a red parallel plano-convex striped cylindrical lens, called a Maddox Rod lens, a streak of red light is viewed by one eye, whereas the fellow eye views a fixation spot produced by a penlight.<sup>8</sup>

Tests that require patient responses are considered *subjective*.<sup>14-17</sup> Tests that do not require subjective responses are considered *objective*.<sup>17,18</sup> Nevertheless, in the cover test that is considered objective, the measurement is dependent on the examiner judgement. It has been shown<sup>9,19</sup> that the clinician's experience affects the results of the cover test and that the examiner endpoint criteria varies amongst individuals.<sup>20</sup> Therefore the cover test cannot be considered fully objective.

An eye tracker that detects and quantifies eye position can be used for fully objective, nonhuman dependent assessment of eye position. Measurements of heterophoria using an eye tracker were previously carried out by several groups. Peli and McCormack<sup>21</sup> examined the dynamics of cover test eye movements using an electromechanical occluder driven by a motor. They reported significant differences between the right and left eyes under the cover only for subjects with strong ocular dominance. Barnard and Thompson<sup>22</sup> reported significant differences in the heterophoria value measured with two versus ten seconds' occlusion duration using stepper-motor driven occluders, one for each eye. Goltz et al.<sup>23</sup> examined the dissociated vertical deviation at three positions of orientation with the use of a video-based eye tracker and manual occlusion with manual recording of the occlusion duration. They reported that certain neck postures can affect the vertical heterophoria value. Hrynychak et al.<sup>9</sup> did not find significant differences ( $<2$  prism diopters [PD] for all conditions) between heterophoria measurements of 50 participants undertaken by two novice third-year optometry students, two optometry faculty members with 25 years of experience, and an objective head-mounted, 120-Hz video-based eye tracker. Babinsky et al.<sup>2</sup> reported the normative values of heterophoria using an IR-filter as a cover over the right eye and a 25-Hz PowerRefractor recording of the eye position. The PowerRefractor has also been used by others to objectively assess heterophoria in children<sup>24</sup> and adults.<sup>3</sup> Recently, an automated system of eye tracking at 60 Hz with a synchronous controlled sliding occluder for cover testing has been reported.<sup>25</sup> However, some of these studies did not assess the differences between this objective test and standard clinical tests. Some also did not examine the differences in heterophoria

values measured when different eyes are covered, or the effect of cover duration. In a recent publication,<sup>26</sup> the EyeLink 1000 Plus (SR Research Ltd., Ontario, Canada) was used in combination with IR-filter and cross-polarized occluder driven by a stepper motor. The setup required a chinrest that can both introduce a burden for participants and is not as easily implemented in clinical practice, but provides increased accuracy relative to the unrestrained conditions.<sup>27</sup> In the study, heterophoria during occlusion of the right versus left eyes of 30 participants was compared. The eye tracker was also validated against the clinical cover test and the Maddox with Thorington Card clinical measurements. The authors reported that the eye tracker consistently measured lower values and was not interchangeable with the clinical measurements. It also showed high intrasession and intersession repeatability results compared to clinical tests. Finally, the authors reported statistically but not clinically significant differences between the heterophoria value measured when the right versus left eye was covered. In that study, the IR cover used was not synchronized with the eye tracker to obtain accurate cover duration information, the target used for eye tracking was not identical to the target used in the clinical heterophoria measurements, and the cover duration was not assessed. Still, the study highlights the advantage of using objective eye tracking for clinical outcome measurements.

Despite their efficiency and objectivity, eye tracker based heterophoria measurements have not been adapted for broad clinical use. Currently, eye trackers can be found in many commercial, nonresearch, applications. Although a decade ago the cost of a basic eye tracker was more than \$10,000 US, today an eye tracker with a frame rate of more than 100 samples per second is available for leisure video games with a price tag of \$200 US. The use of an eye tracker for heterophoria measurements requires integration with a removable optical element that can produce dissociation in the views of the two eyes.

The objective of this study is to demonstrate that using a simple IR detector combined with an off-the-shelf video-based eye tracker in unrestrained conditions, can be synchronized with a handheld removable optical element for fully objective heterophoria testing. The proposed setup was validated against the broadly used cover test at various testing conditions.

The optical element integrated into this system is an IR pass filter that occludes one eye's view while simultaneously enabling tracking of the eye's position under the cover using the video eye tracker. The optical IR filter was mounted on a handheld paddle with a miniature sensor that is sensitive to IR light. When the paddle with the optical filter and sensor is placed in front of

the eye, the sensor detects the IR illumination of the eye tracker. The binary reading from the IR sensor is used to synchronize the eye data with the placement of the IR filter in front of the eye. In this research study, we implemented this straightforward synchronization to examine parameters related to the clinical cover test and their effect on the clinical measurement. Specifically, the cover duration and the eye under the cover were examined. The effect of these variables on the outcomes measured in the cover test was examined herein.

## Methods

### Participants

Thirty healthy volunteers above the age of 18, with a corrected distance Snellen visual acuity of at least 20/40, near visual acuity of J1, and at least 40'' stereoacuity (Paul Harris Randot stereotest, Bernell, Mishawaka, IN, USA) were recruited to the study. Participants with a history of strabismus, amblyopia, or visual therapy for binocular visual disorders were excluded. Participants with a vertical heterophoria on cover testing were also excluded. The study was approved by the internal ethics review board at Hadasah Academic College. The experimental procedures were orally explained, and participants signed a statement of informed consent prior to their participation.

### Experimental Setup

The SMI Red250 Hz infra-red (IR) eye tracker has been previously validated in other studies.<sup>28–31</sup> The Red250 eye tracker was used at 250 Hz. As seen in Figure 1, participants sat at a distance of 40 cm from an independent 1920 × 1080 pixel monitor displaying the stimulus. The eye tracker was attached to a free-standing carrier and was placed at a distance of 60 cm from the participant based on manufacturer recommendations. Each participant underwent the standard five-points calibration, under binocular viewing conditions, in which both eyes were instructed to follow a spot target to known positions along the computer monitor, prior to heterophoria measurement. The ET heterophoria was quantified by recording eye position while the eye was covered with a handheld IR filter attached to a handle that was synchronized with the ET (Fig. 2).

As depicted in Figures 2 and 3, the 50-mm diameter IR-pass filter (RG-780, p/n 66-104 Edmund Optics, Barrington NJ, USA) blocked the visible light and allowed the passage of IR light. This enabled the ET



**Figure 1.** Experimental setup for eye tracking part of experiment. Participants sat at a distance of 40 cm from the monitor. The IR filter was placed in front of the eye by the examiner and was synchronized with the eye tracker, attached to a free-standing carrier at a distance of 60 cm (ET).

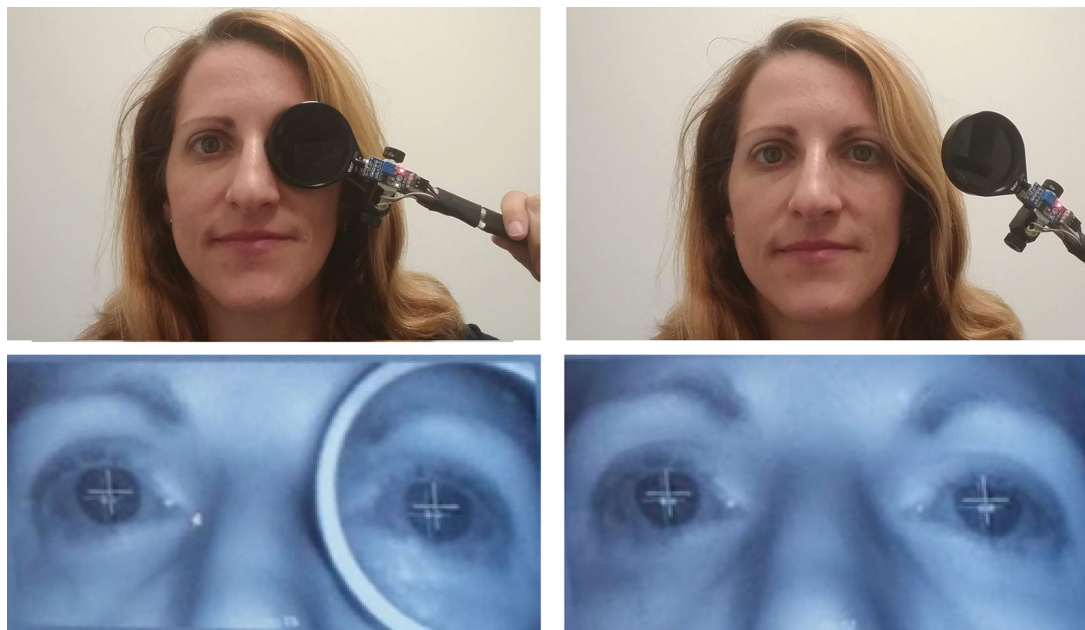
to acquire images of both the covered and uncovered eyes. An IR detector with the attached circuit (IR Infrared Flame Detection Sensor Module, eBay.com) was attached to the IR pass handle. The sensitivity of the sensor module was adjusted to output a TTL signal in the presence of the IR illumination of the eye tracker, indicating that the occluder is in front of the eye. The handle also included a two-position switch that was used by the examiner to indicate the covered eye. The position of the switch and the output of the IR sensor module were routed to the LPT1 input of the PC and recorded on the SMI ET output. This allowed synchronization with the eyes' position.

Custom MATLAB (Version R2018B) was used to create plots of eye position over time for each of the two eyes. Due to the synchronization with the occluder, the MATLAB program plotted the position of the cover in the eye movement trace. Heterophoria is often defined as a relative deviation between the eyes.<sup>26</sup> Adopting this definition, the difference between the left and right eye position was calculated and traced. The heterophoria was calculated as the difference between the binocular eye position during the occlusion time as opposed to the binocular eye position during binocular viewing, that is, fusion, as detailed in the following equation:

$$\Delta_{\text{Heterophoria}} = \Delta_{\text{Fusion}} - \Delta_{\text{Cover}}$$

Where  $\Delta_{\text{Cover}}$  is the mean binocular eye position during the occlusion time that is averaged over three seconds and  $\Delta_{\text{Fusion}}$  is the mean binocular eye position averaged over three seconds of binocular viewing (fusion).





**Figure 2.** Handheld IR-pass filter occluder. The IR-pass filter allows transmittance of IR light while blocking visible light. An IR sensor was attached to a handle that was synchronized with the ET. *Upper panel* demonstrates the position of the occluder relative to the eye: *left*: no-fusion, *right*: fusion. The *lower panel* shows the images of the eyes as detected by the eye tracker with the occluder (*left*) and without the occluder (*right*).

## Experimental Procedures

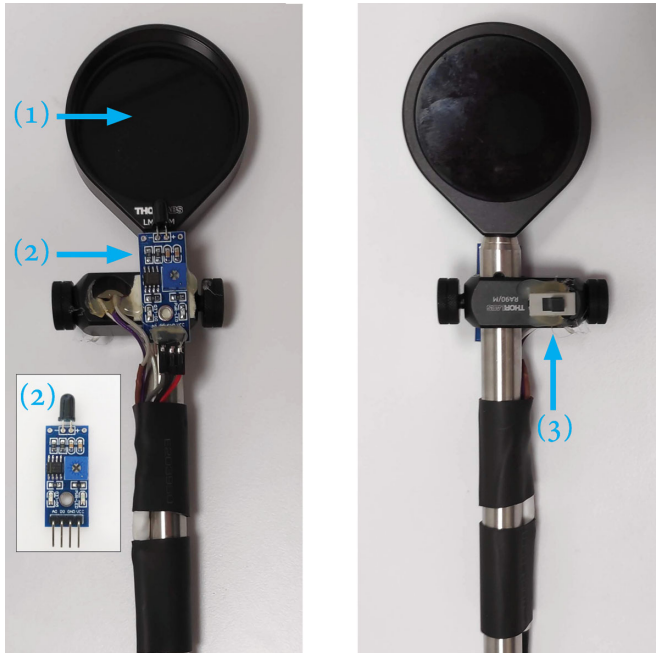
After undergoing initial clinical tests to verify inclusion criteria, participants underwent a clinical near cover test (CT) and eye tracker (ET) testing in pseudo-random order, such that half were initially examined with a CT and half were initially examined with the ET. During testing, participants wore their habitual visual correction. CT was performed three times in consecutive order, in the same examination lane for all participants, at a distance of 40-cm with dim lighting and a penlight as a target, to approximate the ET test target. All participants were first examined with the cover-uncover procedure followed by the alternating cover procedure. In the alternating cover procedure, a prism bar was used to quantify the heterophoria. The prism bar (Gulden Ophthalmics, Elkin Park, PA, USA) had powers of 1, 2, 4, up to 20 PD in 2 PD steps, with subsequent prism powers of 25 to 45 PD in 5 PD steps. This measurement was performed similarly to the standard clinical procedure. The examiner covered each patient's eye and alternated the cover between the eyes at least three times while placing a prism bar in front of a randomly selected eye until no movement is detected. However, all alterations were performed at one sitting, such that only a single clinical CT value was recorded.

Each participant underwent ET cover testing of either the left or right eye, for durations of three

seconds or ten seconds. Every experimental condition was repeated three times for each participant, and the mean heterophoria measurement was computed.

## Statistical Analysis

The mean heterophoria measurement of the right versus left eye for each condition (three seconds versus ten seconds) was compared, and the mean heterophoria measurement for the three vs. ten second cover duration for each condition (right eye vs. left eye) was compared. Numeric data were presented as mean plus or minus standard deviation. Normality was assessed using the Anderson-Darling normality test. Normally distributed data were compared by use of paired *t*-tests, whereas abnormally distributed data were compared by use of a nonparametric Wilcoxon signed paired rank test. The CT versus ET measurements were assessed for interchangeability using Pearson's correlation analysis, and if significant, they were subsequently analyzed using Bland and Altman analysis. Bland and Altman graphs were created by plotting the difference between the measurements against the mean of the measurements. Nonnormally distributed data<sup>32</sup> were compared by using an interval range of  $\pm 2$  PD based on the clinical range of resolution reported in previous studies.<sup>33,34</sup> In cases where subjects with exophoria varied in behavior from subjects with esophoria,



**Figure 3.** IR-Pass Filter and IR detector include (1) 50 mm diameter IR-pass filter that blocks the visible light and passes the IR light to enable the ET to acquire images of both the covered and uncovered eyes in all conditions; (2) IR detector with the attached circuit. The sensitivity of the sensor module was adjusted in order to output a TTL signal in the presence of the IR illumination of the eye tracker that indicated that the occluder is in front of the eye; (3) A two-position switch was used by the examiner to indicate the covered eye. The position of the switch and the output of the IR sensor module were routed to the LPT1 input of the PC and were recorded on the SMI ET output. This was synchronized with the eyes' positions.

separate plots were created for each subgroup. The cutoff for statistical significance was considered as  $P < 0.05$ . All statistical analyses were performed using MATLAB (MathWorks, Inc., Natick, MA, USA).

## Results

Thirty nonpresbyopic volunteers (11 males, mean age  $24.50 \pm 2.2$ , range: 20–28) with a mean Snellen decimal distance visual acuity of  $0.93 \pm 0.09$  ranging between 0.80 to 1.02 (Snellen decimal), all with near visual acuity of J1+ and 20" stereopsis, participated in the study. The heterophoria values measured using the cover test procedure ranged from 14 PD exophoria to 4 PD esophoria. Twelve participants had heterophoria values larger than 4 PD exophoria, and four participants had heterophoria values larger than 1 PD esophoria.

Figure 4 presents ocular traces from a representative participant. The upper left panel shows the left eye

covered for 3.2 seconds, and the deviation of the left eye to its heterophoric position under the cover. The upper right panel shows the right eye almost steady in its primary position during fixation of the target. The upper middle panel shows the difference between the positions of the right eye and the position of the left eyes, which was used to calculate the heterophoria. The upper panel difference of 52 pixels was equivalent to 3.18 PD exophoria. In the lower panels, the right eye (seen in the rightmost panel) is covered for 10.8 seconds. The left eye (seen in the left panel) is almost steady in its primary position during fixation. The middle panel shows the difference in the position of the right and left eyes, 70 pixels, which is equivalent to 4.28 PD.

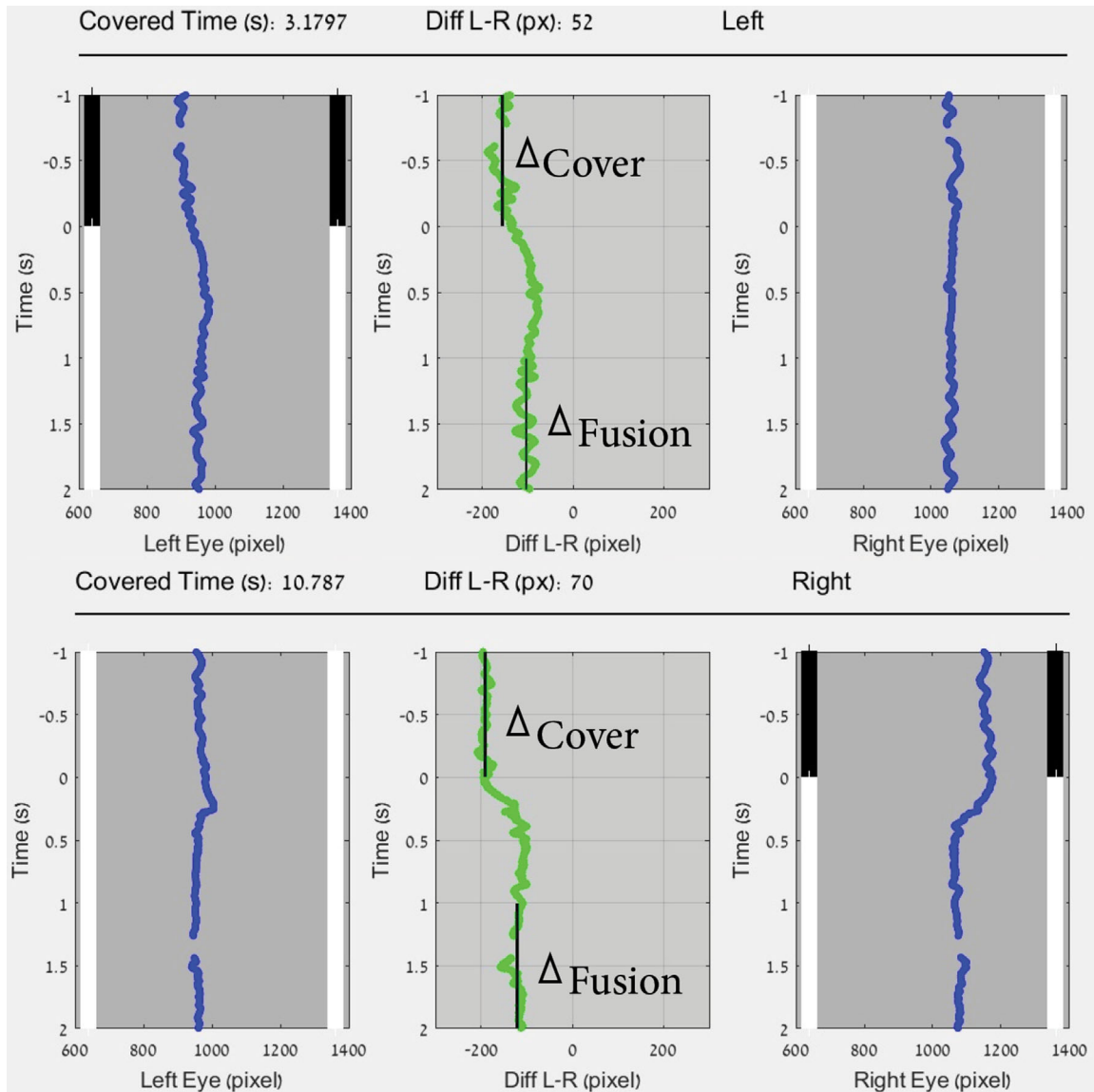
The Table lists the mean findings for clinical cover testing and the various conditions for ET measurements. The difference between the cover test and each of the ET conditions is listed in the bottom row of the table. The left eye position for ten seconds of occlusion of five participants was not recorded by the eye tracker and was not included in the analysis. This condition has been marked with an asterisk in the results displayed below.

## Influence of Covered Eye

Correlation plots comparing the heterophoria measurement of the left eye [LE] occlusion as a function of the measurement for right eye [RE] occlusion are shown in Figures 5A and 5C for the three- and ten-second cover durations, respectively. The eye tracking heterophoria measurements for the right eye cover versus left eye cover, and left eyes were significantly correlated for both cover durations. Pearson correlation coefficients were  $R = 0.98$  for the three seconds' cover duration and  $R = 0.94$  for the ten seconds duration (both  $P < 0.0001$ ).

The data were not normally distributed based on the Anderson-Darling normality test (3 s:  $P = 0.02$  for both eyes, 10 s:  $P = 0.008$  for the right eye,  $P = 0.02$  for the left eye). Therefore the nonparametric Wilcoxon signed paired rank test was applied to examine the difference between the heterophoria measurements under different cover conditions.  $P$  values for the differences between the LE and RE cover conditions were  $P = 0.48$  and  $P = 0.86$  for the three and ten seconds' cover durations. Hence, the test fails to reject the null hypothesis of zero median in the difference at the default 5% significance level. As such, we can assume that heterophoria measurements when RE or LE are covered, are interchangeable.

Bland and Altman plots of the difference of heterophoria measurements between LE versus RE



**Figure 4.** Eye movement trace analysis of one participant obtained from MATLAB software analyzing the SMI Red250 Eye Tracker output. The left eye (*left panels*) and right eye (*right panels*) positions are plotted as a function of time. The black bars, at the sides of the eye trace plots, mark the duration of the cover (also stated above the panels as "Covered Time"). The *upper panels* demonstrate 3-second cover condition of the left eye covered, and the *lower panels* demonstrate 10-second condition of the right eye covered. The actual time that the eye was covered was measured by the software and is plotted for verification. In both cases, the fellow eye that is uncovered maintains a steady position during fixation. The middle plots show the difference between the right and left eye positions, which is used to calculate the heterophoria.  $\Delta_{Cover}$  is the mean binocular eye position during the occlusion time, which is averaged over three seconds,  $\Delta_{Fusion}$  is the mean binocular eye position during binocular viewing (fusion). In the *upper panels* the difference of 52 pixels was equivalent to 3.18 PD exophoria. In the *lower panels*, the difference of 70 pixels was equivalent to 4.28 PD.

occlusion against the mean measurements, per subject, are shown in [Figures 5B](#) and [5D](#) for the three and ten seconds' cover durations, respectively. The mean difference between the right eye and left eye conditions was lower than 0.2 PD for both three (0.04 PD) and ten seconds' (0.12 PD) cover durations. The difference for 53 out of 55 total measurements (>95%) were lower than the clinical range of agreement of  $\pm 2PD$ .<sup>33,34</sup>

### Influence of Cover Duration

The left eye data was missing values for the ten seconds cover duration for five participants. Therefore this dataset included 25 eyes. Correlation plots comparing the heterophoria measurement of the ten seconds' cover duration as a function of the measurement of the three seconds cover duration are shown in [Figures 6A](#)

**Table.** Mean Heterophoria Measurements Using Two Methods

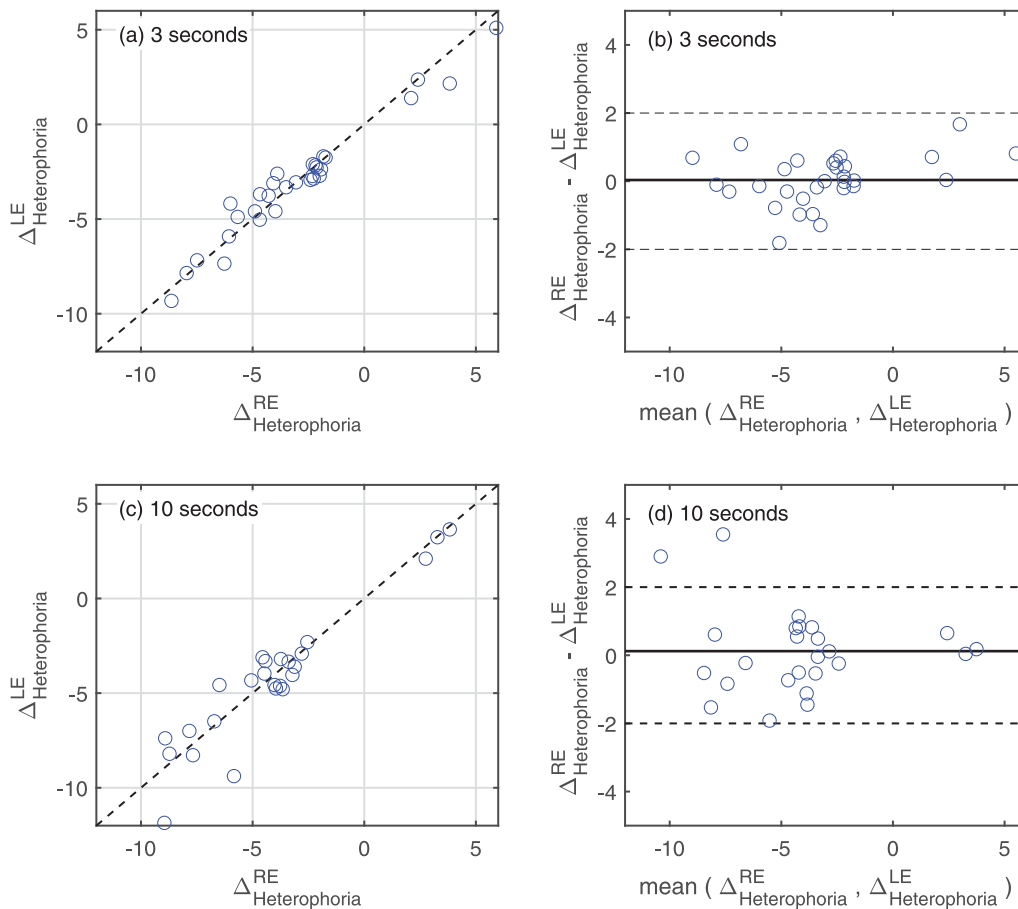
CT	Right Eye ET		Left Eye ET	
	3-second cover	10-second cover	3-second cover	10-second cover
$4.27 \pm 3.96^\Delta$	$-3.07 \pm 3.30^\Delta$	$-4.03 \pm 3.87^\Delta$	$-3.10 \pm 3.05^\Delta$	$-4.28 \pm 3.58^\Delta$
Difference relative to CT	$1.20^\Delta$	$0.24^\Delta$	$1.17^\Delta$	$0.01^\Delta$

and 6C for the RE and LE, respectively. The heterophoria measurements for the three and ten seconds' cover durations were significantly correlated. Pearson correlation coefficients were  $R = 0.97$  for the RE and  $R = 0.96$ , for the LE (both  $P < 0.001$ ).

The data were not normally distributed based on the Anderson-Darling normality test as stated above. Similarly, the nonparametric Wilcoxon signed paired rank test was applied to examine the difference between the heterophoria measurements under different cover

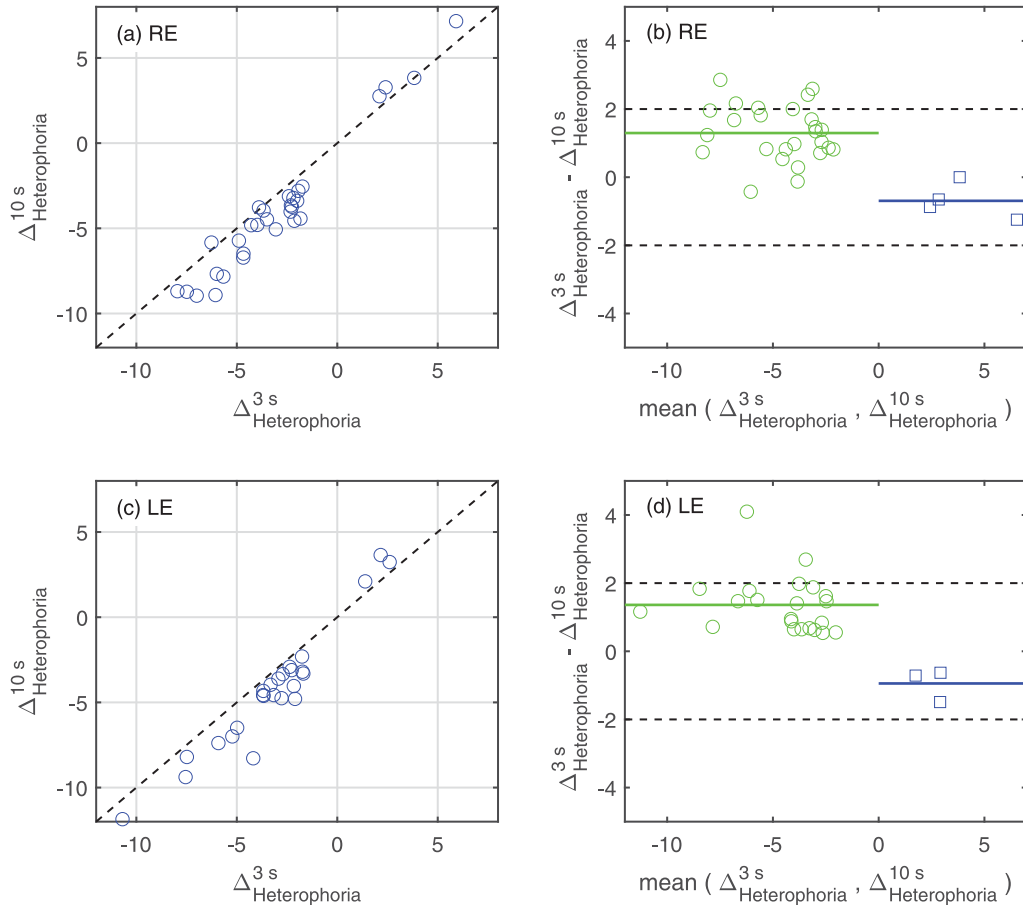
conditions.  $P$  values for the differences between the three and ten seconds cover durations were  $P < 0.001$  for both RE and LE cover conditions. Hence, the test rejects the null hypothesis of zero median. At such, the heterophoria measurements at different cover durations are significantly different.

For positive heterophoria values, that is, esophoria, the measurements with longer cover duration are higher, whereas for negative heterophoria values, that is, exophoria, the measurements with longer cover



**Figure 5.** Comparison of the occluded eye. Correlation plots of the heterophoria measurements during occlusion of the left eye as a function of the occlusion of the right eye for 3 s (a) and 10 s (c) cover durations. The dashed line represents the one-to-one correlation. Bland and Altman plots representing the difference between heterophoria measurements during right eye occlusion and left eye occlusion for for 3 s (b) and 10 s (d) cover durations. The black line represents the mean difference, whereas the dashed lines show  $\pm 2$  PD, which are the upper and lower clinical resolution limits. Each data point represents one participant. All values presented are in prism diopters.





**Figure 6.** Comparison of cover duration. Correlation plots of heterophoria measurements using the 10 s cover duration as a function of the measurement with 3 s cover duration for right (a) and left (c) eye occlusion. The dashed line represents the one-to-one correlation. Bland and Altman plots representing the difference between heterophoria measurements between 3 and 10 seconds of cover durations as a function of the mean measurement for right (b) and left (d) eye occlusion. Green unfilled circles represent exophoric values and blue unfilled squares represent esophoric values. The green and blue lines represent the mean difference between the conditions. The dashed lines show  $\pm 2$  PD, which are the upper and lower clinical resolution limits. Each data point represents one participant. All values presented are in prism diopters.

duration are lower. As such the difference in the esophoria and exophoria measurements, in Figures 6B and 6D are shown separately for the two subgroups. The mean difference between the cover durations for the right and left eyes were 1.4 PD and 1.3 PD, respectively, for the exophoric subjects. The mean difference between the cover durations for the right and left eyes were  $-0.7$  PD and  $-0.9$  PD, respectively, for the esophoric subjects. Nonetheless, the difference for 49 of 55 total measurements ( $>89\%$ ) were lower than the clinical range of agreement of  $\pm 2$  PD.<sup>33,34</sup>

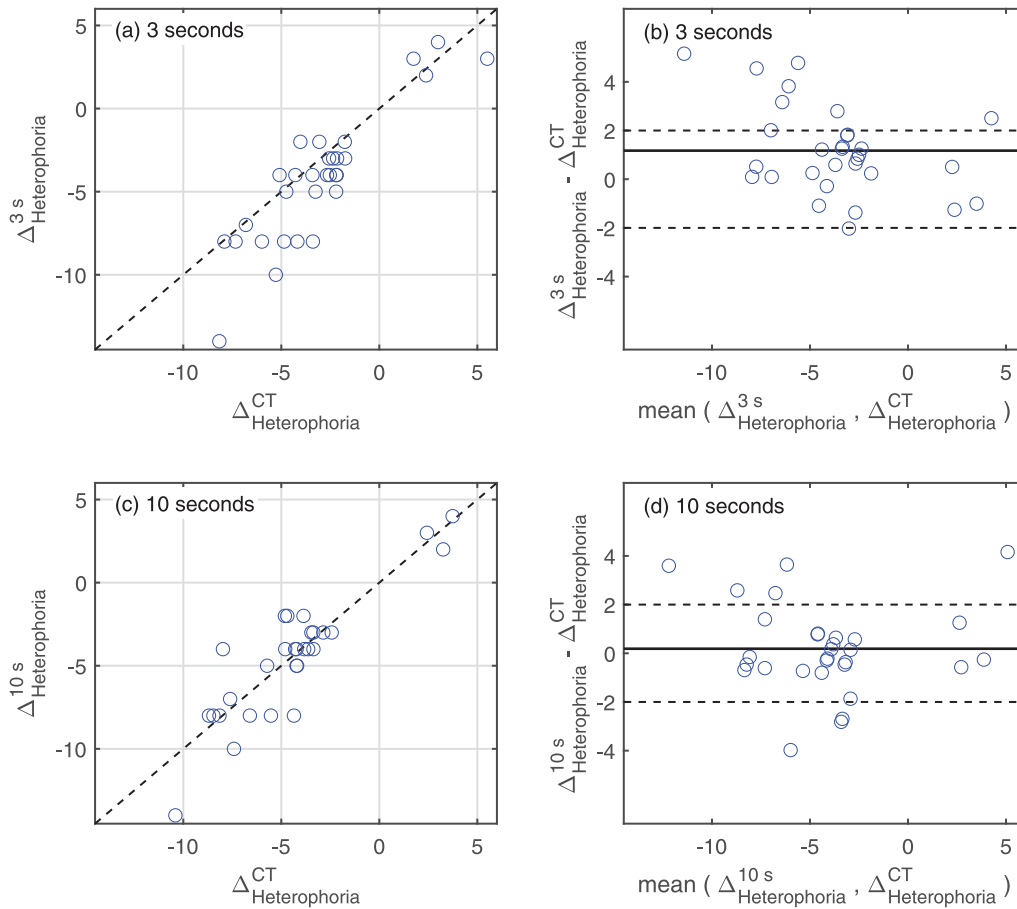
### Comparison Between Clinical CT and ET

As reported above, the heterophoria measurements with the RE vs. LE covered are not significantly different. Therefore, in the comparison with the clinical CT

we used the mean of the two measurements, i.e. RE and LE using the ET setup Data. Correlation plots comparing the heterophoria measurement using the ET as a function of the measurement using the clinical CT for the mean three seconds and ten seconds cover durations are shown in Figures 7A and 7C, respectively. Both cover duration's ET measurements and CT measurements were significantly correlated. Pearson correlation coefficients were  $R = 0.89$  for the three seconds' cover duration and  $R = 0.90$  for the ten seconds' duration (both  $P < 0.00001$ ).

The data were not normally distributed based on the Anderson-Darling normality test as stated above. Similarly, the non-parametric Wilcoxon signed paired rank test was applied to examine the difference between the heterophoria measurements under different cover conditions. The  $P$  value for the differences between the





**Figure 7.** Comparison between the cover test and eye tracker. Correlation plots of heterophoria using ET measurement as a function of the CT measurement for 3 s (a) and 10 s (c) of cover duration. The dashed line represents the one-to-one correlation. Bland and Altman plots of the difference between the of ET and CT test measurements plotted as a function of the mean of ET and CT measurements for 3 s (b) and 10 s (d) of cover duration. The solid lines represent the mean difference between the conditions. The dashed lines show clinical range of agreement. Each data point represents one participant. All values presented are in prism diopters.

three seconds cover duration ET measurements and cover test measurements was  $P = 0.0011$ . Hence, the test rejects the null hypothesis of zero median for the three seconds' duration ET measurement compared to the CT measurement and they are considered significantly different. The  $P$  value for the differences between the ten seconds' cover duration ET measurement and cover test measurements was  $P = 0.52$ . The test fails to reject the null hypothesis of zero median in the difference at the default 5% significance level. As such, based on our data, there is no significant difference between the ten seconds' cover duration ET and CT measurements.

Bland and Altman plots of the difference between the heterophoria measurements using three seconds and ten seconds ET and clinical CT measurements as a function of their mean measurement are shown in Figures 7B and 7D, respectively. The data for the

ten seconds' cover duration included only right eye measurements for five observations, and the mean of the two eye measurements for the remaining 25 observations.

The mean difference between the three and ten seconds' cover duration ET measurements and cover test measurements was 0.26 PD and 1.22 PD, respectively. For both conditions, the mean difference was lower than the clinical range of agreement of  $\pm 2$ PD. The difference for 41 of 60 total measurements (77%) were lower than the clinical range of agreement of  $\pm 2$ PD.<sup>33,34</sup> Nonetheless, this amount of observations outside the clinical range of agreement is too large to be considered interchangeable.

There was agreement in terms of the *direction* of the heterophoria between the ET and CT in *all* participants, for both cover duration measurements.

## Discussion

The results presented herein demonstrated the feasibility of a simple objective heterophoria measurement using unrestrained eye tracker that can be implemented clinically. The proposed device incorporated synchronizing a simple and inexpensive optical element such as an IR pass filter with an inexpensive IR eye tracker.

A direct comparison with the widely used cover test is challenging. Although the cover test is considered an objective clinical test, it is influenced by clinician experience and endpoint criteria. In practice, cover durations vary between clinicians. Incorporating an eye tracker in the clinic, as in the current configuration, in which the cover is synchronized with the tracker, allows objective and consistent measurements. To demonstrate the consistency of the heterophoria measurement, several testing conditions were compared using the eye tracker setup. For each participant, left versus right eye cover and short versus long cover durations were compared.

Results showed that there was no statistical or clinical difference between the outcome measurements when the right vs. left eye was covered. There was a statistically but not clinically significant effect of three versus ten seconds' cover duration. The CT and the ten-second cover duration ET were not statistically or clinically different. The CT and three-second cover duration ET were found to be statistically but not clinically different.

We implemented the Bland and Altman nonparametric approach to compare data that are not normally distributed.<sup>32</sup> Specifically, the clinical resolution of  $\pm 2$  PD was used as the limit of agreement in the Bland and Altman plots. Two prism diopters are considered by many studies as the smallest deviation that can be detected under ideal conditions by human observers.<sup>33,34</sup> As such, differences between measurements that are smaller than 2 PD can be considered clinically insignificant. Based on these assumptions, six and eight observations were outside the clinical range of agreement in the comparison between ten seconds' ET cover duration and three seconds' ET cover duration versus CT measurements, respectively.

The larger discrepancy between the three seconds' cover duration versus CT may be due to the nonstandardized CT conditions, with uncontrolled cover durations. The clinical CT cover duration was not controlled to simulate real world conditions, similarly to other studies, as tabulated in the Supplementary Material. In addition, the lack of agreement could be due to inaccuracies in eye position or loss of data<sup>27</sup> that

can occur in unrestrained ET conditions. Future experiments can examine the agreement between ET recordings under restrained versus unrestrained conditions. Less agreement was reported for higher magnitudes of measurement by Mestre et al.<sup>26</sup> One possible reason could be the number of participants presenting with larger magnitudes of heterophoria. Larger exophoria at near and certainly esophoric values at near viewing are less common in the population in general<sup>35</sup> and also in the sample included in this study, which results in larger variability.

## Cover Duration

Duration of dissociation has been reported to affect subjective heterophoria measurements in nearly seven of 16 participants, whose heterophoria was more than 3 PD more exophoric with prolonged dissociation.<sup>16</sup> Barnard<sup>36</sup> reported clinically insignificant heterophoria measurements for two-second versus ten-second cover durations, although the heterophoria measurement for longer cover durations tended to be higher values. Similarly, also the current study did not find statistical or clinical differences between the three seconds' and ten seconds' cover duration heterophoria measurements and found higher heterophoria values for the longer cover durations. Presumably, the longer cover duration provides longer dissociation, which can allow the heterophoria to drift to its final position. This is an important consideration for clinicians, because many binocular visual anomalies are accompanied by large heterophoria values.<sup>17</sup>

## Effect of Eye Under Cover

Peli and McCormack<sup>21</sup> reported dissimilar heterophoria values with the covered eye only when there was a clearly dominant eye. Mestre et al.<sup>26</sup> reported significant differences between heterophoria values measured with the right versus left eye covered, although the differences were smaller than 1 PD, which is not clinically significant. They also did not find a significant correlation between heterophoria value and the dominant eye. Similarly, the current study found a mean difference of 0.04 PD and 0.12 PD between the right and left eye cover measurements for three versus ten seconds' cover durations, respectively. These values were not significantly different statistically or clinically.

## Intra Session Repeatability

Although not a direct purpose of the study, because of the repeated measurements obtained with the ET it is possible to examine the intrasession repeatability

by examining the standard deviation of the measurements. All standard deviations were smaller than 4 PD, with the smallest standard deviation measured for the three second cover duration of the left eye (3.19 PD) and largest for the 10-second cover duration of the right eye (3.93 PD). These values are larger than the intrasession repeatability reported with the EyeLink 1000 Plus 250 Hz ET, which was approximately 1 PD.<sup>26</sup> This discrepancy may be due to the fact that the standard deviation reported using the EyeLink was the mean of six measurements, whereas the value in this study is the mean of three measurements. It could also be due to the fact that subjects in the EyeLink experiment were restrained with a chin rest whereas subjects in the present study were unrestrained.

## Target Type

Target characteristics can affect results of clinical tests such as fused cross cylinder.<sup>37</sup> Near point of convergence has been reported by some to vary with target type,<sup>38</sup> although not by others.<sup>39</sup> Clinical cover tests with accommodative versus nonaccommodative targets were not found to be significantly different clinically.<sup>40</sup> Similarly, standard heterophoria testing and power refractor objective testing of heterophoria with movies vs. a standard clinical target did not result in significant differences.<sup>24</sup> As such, we can assume that the use of a penlight for our cover testing and ET protocol yield similar results to accommodative targets, but future investigations should include a systematic comparison of target type and its effect on subjective and objective heterophoria testing.

## Conclusion

This study demonstrated the feasibility of measuring the heterophoria using an inexpensive IR eye tracker combined with a hand-held IR pass filter that dissociates between the eyes while simultaneously synchronizing with the video recording. Using this system, we were able to show that the differences in heterophoria measured when the right as opposed to the left eye is covered in the clinical cover test are not significantly different clinically. However, cover test duration can impact the measurement, especially short duration. Hence, the cover duration should be standardized in the clinical setting, possibly with a relatively simple setup such as suggested in this study. The current setup was demonstrated in adults. Given its unrestrained setup, the system allows measurement

under natural viewing with the potential to be used on children.

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