Journal of Optometry (2019) 12, 222–231

Journal of Optometry

www.journalofoptometry.org

ORIGINAL ARTICLE

Does an iPad fixation disparity test give equivalent results to the Mallett near fixation disparity test?

Ketan R. Parmar[a,*], **Christine Dickinson**[a], **Bruce J.W. Evans**[a,b]

[a] *Division of Pharmacy and Optometry, School of Health Sciences, Faculty of Biology, Medicine and Health, University of Manchester, Manchester Academic Health Science Centre, Manchester, UK*
[b] *Institute of Optometry, 56-62 Newington Causeway, London SE1 6DS, UK*

Received 24 October 2018; accepted 21 March 2019
Available online 7 September 2019

KEYWORDS
Fixation disparity;
Associated phoria;
Aligning prism;
Mallett unit;
Nonius markers

Abstract
Background: Various instruments have been developed to measure aligning prism, the prism that eliminates a fixation disparity (associated heterophoria). This includes the established Mallett near vision unit and recently developed Thomson Vision Toolbox on the iPad. With no previous research investigating the agreement between these instruments, practitioners may question if they can be used interchangeably.
Methods: 80 participants underwent near vision testing with the Mallett unit and iPad fixation disparity test. Data were analysed in four ways to investigate the agreement of the two instruments.
Results: Many participants reported no fixation disparity (horizontally 46.25%, vertically 82.5%), or non-significant aligning prism (horizontally 70%, vertically 97.5%), on both instruments. The iPad revealed a larger range of aligning prism results horizontally, 6Δ base out to 15Δ base in; the Mallett unit produced a larger range of results vertically, 1Δ base up to 3.5Δ base down. More participants required a significant aligning prism on the Mallett unit horizontally and vertically. Wilcoxon signed rank analysis found that the difference in aligning prism was not statistically significant ($p = 0.357$ horizontally, $p = 0.236$ vertically), but 95% limits of agreement revealed clinically significant differences between the instruments.

* Corresponding author at: Division of Pharmacy and Optometry, School of Health Sciences, Faculty of Biology, Medicine and Health, University of Manchester, Manchester Academic Health Science Centre, Manchester, UK.
E-mail address: ketanparmar@live.co.uk (K.R. Parmar).

https://doi.org/10.1016/j.optom.2019.03.002

Conclusion: Although the measured differences between the instruments are not significant in a Wilcoxon analysis, a Bland & Altman approach shows them to be in some cases clinically unacceptable, therefore the instruments should not be used interchangeably. Previous research indicates that the Mallett unit performs reasonably well at detecting symptomatic individuals and determining a prismatic correction that is likely to be helpful. Further research is required to determine the performance of the iPad test in these functions and to assess the reproducibility of both instruments.

PALABRAS CLAVE
Disparidad de fijación;
Foria asociada;
Prisma de alineamiento;
Unidad de Mallett;
Marcadores Nonius

¿Puede aportar la prueba de disparidad de fijación en iPad unos resultados equivalentes a la prueba de disparidad de fijación de cerca de la unidad de Mallett?

Resumen
Antecedentes: Se han desarrollado diversos instrumentos para medir el prisma de alineamiento, que es el prisma que elimina la disparidad de fijación (heteroforia asociada). Entre estos instrumentos se incluyen la unidad de visión de cerca de Mallett y la recientemente desarrollada Thomson Vision Toolbox en el iPad. Como no existe investigación previa acerca del acuerdo entre estos instrumentos, los clínicos pueden cuestionarse si pueden usarse ambos tests de forma intercambiable.
Métodos: Se realizó una prueba de visión de cerca a 80 participantes, utilizando la unidad de Mallett y la prueba iPad de disparidad de fijación. Los datos fueron analizados de cuatro modos, para evaluar el acuerdo entre ambos instrumentos.
Resultados: Muchos participantes reportaron ausencia de disparidad de fijación (horizontalmente 46,25%, verticalmente 82,5%), o prisma de alineamiento no significativo (horizontalmente 70%, verticalmente 97,5%), con ambos instrumentos. El iPad reveló un mayor rango de resultados de prisma de alineamiento horizontalmente, 6Δ base externa con respecto a 15Δ base interna, y la unidad de Mallett produjo un rango mayor de resultados verticalmente, 1Δ base superior con respecto a 3,5Δ base inferior. Muchos participantes requirieron un prisma de alineamiento significativo en la unidad de Mallett horizontalmente y verticalmente. La prueba de rango con signo de Wilcoxon encontró que la diferencia en cuanto a prisma de alineamiento no era estadísticamente significativa ($p = 0{,}357$ horizontalmente, $p = 0{,}236$ verticalmente), pero el 95% de los límites de acuerdo revelaron diferencias clínicamente significativas entre los dos instrumentos.
Conclusión: Aunque las diferencias de las mediciones entre ambos instrumentos no son significativas con el analisis de Wilcoxon, los analisis con Bland & Altman muestran algunas casos clinicamente significativos, y por tanto los instrumentos no deberían usarse de manera intercambiable. La investigación previa indica que la unidad de Mallett tiene un rendimiento razonablemente bueno para detectar los individuos sintomáticos, y determinar una corrección prismática que pueda resultar útil. Es necesaria más investigación para determinar el rendimiento de la prueba iPad en estas funciones y para analizar la reproducibilidad de ambos instrumentos.

Introduction

Good binocular vision requires alignment and coordination of the eyes (motor fusion), the ability of the brain to fuse monocular images (sensory fusion) and appropriate development of the visual system and anatomical features. Poor function of any of these components can lead to a binocular vision anomaly, which can manifest as visual disturbances (e.g., diplopia), asthenopia, or suppression.[1]

The human visual system has evolved to compensate for small disparities in the alignment of the eyes. A fixation disparity describes minute misalignments of the visual axes which do not result in the breakdown of binocular vision because the images fall within corresponding retinal areas (Panum's fusional area).

Panum's area is the retinal area surrounding the horopter within which monocular images can fall whilst binocular vision is maintained. This horizontally oval area varies in spatial size depending on several factors including the area of retinal stimulation; generally increasing with retinal eccentricity from approximately 6 to 10 min of arc at the fovea, to 30 to 40 min of arc at 12 degrees retinal eccentricity.[2]

The theoretical concepts of fixation disparity were established by Ogle and colleagues,[3–5] and it is measured using associative tests. These tests allow some degree of binocular vision with the test target viewed by both eyes, but with parts of the target only seen monocularly through the use of Nonius markers. In comparison to dissociative tests (i.e. those which completely separate the view of each eye with no overlap between the two), associative tests aim to indicate the ability to compensate for heterophoria. Associative tests do not measure the magnitude of the heterophoria, but Mallett designed his fixation disparity test to indicate the component of the heterophoria for which the participant cannot compensate.[6] This has been described as the aligning prism and is also known as the associated heterophoria. In contrast, dissociative tests show little correlation to symptoms as they do not give any information on the ability of the visual system to cope with the heterophoria.[6] Yekta and Pickwell[7] investigated the relationship between heterophoria, fixation disparity, and symptoms. They found no correlation between the magnitude of dissociated heterophoria and symptoms and a poor link between dissociated heterophoria and fixation disparity. However, symptomatic participants required a significantly greater degree of aligning prism than non-symptomatic participants. It is important to note that although Mallett's test identifies the presence of a fixation disparity (a misalignment of the Nonius markers), the fixation disparity is not measured but instead the aligning prism that eliminates the fixation disparity (associated heterophoria) is determined.

A review of fixation disparity tests by Evans[1] noted that research has found the Mallett unit to be useful at predicting symptomatic heterophoria at near, but much less useful at distance, possibly because distance decompensated heterophoria is less commonly encountered. The research described in this paper therefore concentrates on near vision testing only.

Several instruments have been developed to investigate fixation disparity, two of which are the Mallett unit (designed by RFJ Mallett in the 1960s) and the Thomson Vision Toolbox for the iPad.

The method of dichoptic presentation as well as test design of the Thomson Vision Toolbox fixation disparity test has several variations from the original Mallett unit. These include:

- The use of cross-polarised lenses (luminous transmission factor (LTF) = 41.5%) to achieve monocular viewing of the Nonius markers with the Mallett unit but the use of red/green (anaglyph) filters with the iPad design (LTF green filter 6.5%; red filter 10.5%).
- Differences in the central and peripheral fusion locks of both instruments.
- A black background to the fixation markers on the Mallett unit and a grey background on the iPad version.
- A detailed surround (lines of words) on the Mallett unit, and an unpatterned surround on the iPad test.

The Mallett unit is a widely used fixation disparity instrument in the UK,[8] however, the development of the Thomson Vision Toolbox has given practitioners the choice of an iPad fixation disparity test. The Mallett unit was designed with the objective of achieving the most natural viewing conditions, to indicate the ocular motor status under everyday viewing conditions, and so that subsequent tests can be performed without any influence from preceding tests.[6]

Taking into consideration the differences between the Mallett unit and the Thomson iPad fixation disparity test, these variations could affect the results obtained. This issue is important since in some practices there may be an original Mallett unit in one consulting room and the iPad test in another, so equivalence of results is essential if the tests are to be used interchangeably. It is also important for determining whether research regarding norms for the Mallett unit are applicable for the iPad version.[9] This study aimed to investigate the extent to which the results obtained from the conventional Mallett unit agreed with those found on the Thomson Vision Toolbox. This paper evaluates whether the two instruments identify the same participants as having a fixation disparity and, when a fixation disparity is present, the extent to which the two instruments agree concerning the magnitude of the aligning prism.

Materials and methods

The Mallett unit (Mark 2, Gatehouse Scientific Instruments Ltd, Norfolk, UK)

The Nonius markers on the Mallett Unit are cross polarised which coupled with placement of cross polarised filters over the eyes results in each eye only seeing one marker (dichoptic stimulation). All other features of the test are seen binocularly, thus maintaining binocular fusion. Specifically, association is assisted by binocular appreciation of the central fusion lock ''OXO'' and the surrounding text which acts as a peripheral fusion lock (Fig. 1).[6] In a study conducted by Patel,[10] looking into the variations in dimensions on different Mallett units, he found the average dimensions on the mark 2 Mallett units to be as follows; Nonius strip height = 3.4 mm; Nonius strip separation = 3.1 mm; Central fusion lock height = 1.5 mm. When viewed at 40 cm, these equate to a central fusion lock subtending approximately 13 min arc and a Nonius strip separation of ≈27 min arc.

Thomson Vision Toolbox

Professor David Thomson has developed optometric test chart software, including an application for the iPad, with the most recent version released in 2016. The software is ''Vision Toolbox'' which is designed by Thomson Software Solutions Ltd. (Hatfield, UK) for use on an iPad, and therefore presents a range of tests for near vision. This study used version 2.4.1, on an iPad Air 2, model A1566, retina display.

The dichoptic presentation of the markers in this device is achieved by placing a red filter over one eye and a green filter over the other, resulting in only one marker (the opposite coloured one) being seen by each eye. Association is again maintained by both eyes being able to see the central ''432 + 234″ (central fusion lock), the

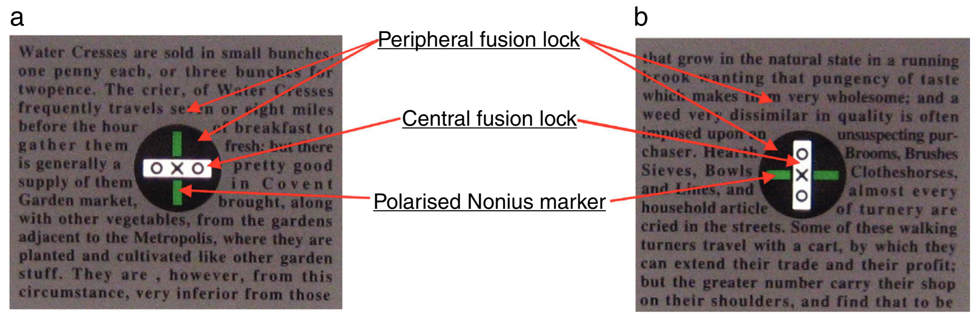

Figure 1 (a and b) The Mallett near fixation disparity test indicating the location of the individual components.[10]

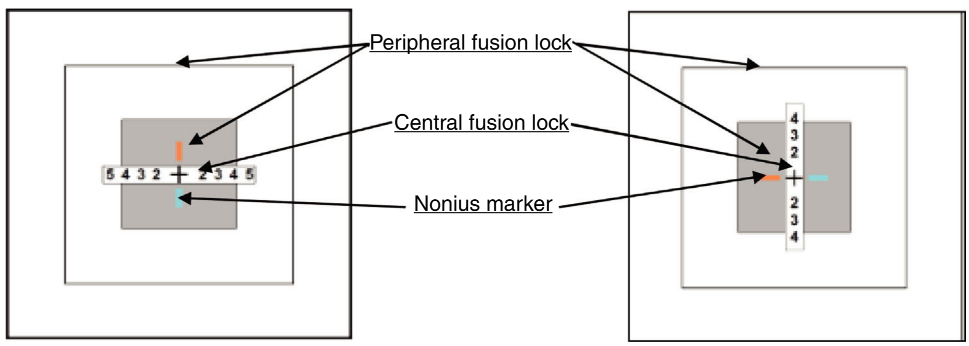

Figure 2 (a and b) An image of the Near Thomson Fixation Disparity test indicating the location of individual components.[11]

surrounding grey area and ''box'' outlines (peripheral fusion locks) (Fig. 2).[11] The dimensions were measured as follows; Nonius strip height = 5.0 mm; Nonius strip separation = 7.0 mm (1 degree at 40 cm); Central fusion lock height = 4.5 mm (39 min arc).

Subjects and procedures

The inclusion criteria were as follows:

- Attending an eye examination at Aarons Optometrists, Ashington, UK.
- Above the age of 16 yrs.
- Non-strabismic on near cover testing.
- Able to resolve N12 print monocularly with each eye.
- Monocular near visual acuity for right eye less than 0.1 LogMAR different from left eye.

This study was given a favourable ethical opinion by the institutional ethics committee at the University of Manchester (Reference number 2017-2607-4106). The nature of the study was explained to each participant, and verbal consent was received and recorded.

Participants undertook the two fixation disparity tests in a random order. Karania and Evans[8] demonstrated that the instructions given during fixation disparity testing are important and influence the results obtained. Their results found that more specific questions as recommended in the literature[12] revealed more cases of fixation disparity and correlated more strongly with symptoms; but this was of significance only for near fixation disparity. The flow chart of questions recommended by Evans[12] and used by Karania and Evans[8] (Figure S1) was used in the present research. Essentially, the participant was asked to focus on the central cross target and to report whether the monocular markers were aligned with the centre of the cross and whether they were moving. If they were misaligned or moving this was corrected with the relevant prism: the aligning prism (associated heterophoria). This procedure was followed for both horizontal and vertical aligning prism measures. Horizontal measures were conducted first, followed by vertical measures, and any required aligning prism was not left in place after it was determined. The required aligning prism was recorded with signs indicating the base direction; ''+'' for base out and base up, ''−'' for base in and base down. Participants were clearly told that they should not assume that the two tests would give the same or a different result but should simply report their observations with each instrument and ignore the results obtained with the first test when being tested with the second test.

The tests took place in a fully lit optometric consulting room as Pickwell et al.[13] reported that poor lighting conditions increased the degree of fixation disparity. Mallett[6] suggested that supplementary lighting, e.g., a lamp, should be directed at the Mallett unit as the polarised filters obviously cause a reduction in light transmission to the eye. No such suggestion can be found in the Thomson Vision Toolbox manual.[11] In this study, the maximum level of consulting room lighting available was used for both tests. An angle poise lamp, if available, was positioned at 30 cm from the Mallett unit, at an angle to avoid glare. The iPad was kept on maximum brightness with the automated brightness setting switched off. The participant was asked to hold the near tests at their preferred working distance (which was measured using a tape measure) perpendicular to their direction

Table 1 The proportion of participants with a horizontal fixation disparity (FD) on each instrument.

	Horizontal FD on Mallett unit	No Horizontal FD on Mallett unit
Horizontal FD on iPad	19 (23.75%)	7 (8.75%)
No Horizontal FD on iPad	17 (21.25%)	37 (46.25%)

Table 2 The proportion of participants with a vertical fixation disparity (FD) on each instrument.

	Vertical FD on Mallett unit	No Vertical FD on Mallett unit
Vertical FD on iPad	2 (2.5%)	6 (7.5%)
No Vertical FD on iPad	6 (7.5%)	66 (82.5%)

of gaze, and to keep this consistent for both tests. Both tests were carried out using any refractive correction that the participant habitually wore for near vision activities.

One of the authors (BJWE) made the anecdotal observation that some participants reported that the blue/green Nonius marker on the iPad test is blurred. To investigate this systematically, all participants were also asked whether they experienced any blurring, flashing, dimming, or other problems with seeing each test, after determining any aligning prism, and these Nonius perceptual anomalies (NPA) were recorded.

Statistical analysis

A repeated-measures design was adopted for this research, with participants undertaking both the Mallett unit and Thomson iPad test. The advantage of this study design is that all subjects serve as their own controls allowing for paired analyses, which increases statistical power and in turn requires a smaller sample size. A search of the current literature revealed no previous research with the iPad test, so the data required for a precise sample size calculation were not available. However, it was calculated that 84 subjects would detect a medium effect size of 0.4 with 0.05 significance and 95% power.

The final results were analysed in four ways. First, the proportion of participants who had zero fixation disparity with each instrument were compared and a 2×2 table was used to determine the extent to which the two instruments classified the same participants as having, or not having, a fixation disparity. Second, following research that identified the magnitude of aligning prism that differentiates symptomatic from asymptomatic participants,[9] further 2×2 tables were used to determine which of the instruments classified participants as requiring a significant degree of aligning prism. A significant fixation disparity was defined as requiring an aligning prism $\geq 1\Delta$ for pre-presbyopes and $\geq 2\Delta$ in presbyopes.[9] Third, for those participants who had a fixation disparity with both instruments the magnitude of aligning prism with each instrument was compared using a Wilcoxon signed ranks test. It was most appropriate to perform a non-parametric test for this study as the results did not follow a normal distribution, as was confirmed by the Kolmogorov–Smirnov test. Finally, the results with each instrument for all participants were compared using Bland and Altman plots.

Results

Data were successfully obtained from 80 participants who ranged in age from 18 to 92 years (mean 49.6 years, median 50.5 years). All participants, except one, required an appropriate refractive correction for the tests and the average working distance was measured to be 38.5 cm (range 26 cm to 50 cm).

Of the two instruments, the iPad revealed a larger range of aligning prism results horizontally, but the Mallett unit produced a larger range of results vertically. Horizontally, participants reported deviations of the Nonius markers from 3 prism dioptres (Δ) base out to 8Δ base in on the Mallett unit, and from 6Δ base out to 15Δ base in on the iPad. Vertically, aligning prism on the Mallett unit was reported from 1Δ base up to 3.5Δ base down, and 1Δ base up to 1Δ base down on the iPad.

Many participants (46.25% horizontally and 82.5% vertically) had no fixation disparity on either instrument (Tables 1 and 2). Of those who did report a horizontal fixation disparity, most (23.75%) found a deviation in the Nonius markers on both instruments, and a larger number of participants reported a misalignment exclusively on the Mallett unit, not the iPad.

In terms of vertical fixation disparity, 82.5% of participants reported no deviation of the Nonius markers on either of the instruments, and very few reported a deviation on both (2.5%). In contrast with the horizontal fixation disparity results, the same number of participants found exclusive vertical fixation disparities on each instrument.

Using the Jenkins et al. (1989) criteria for decompensation,[9] with both horizontal and vertical fixation disparity findings, the majority of participants had non-significant results on both instruments, 70% and 97.5% respectively (Tables 3 and 4). Significant fixation disparity results were found on both or either instrument more frequently horizontally (30%) than vertically (2.5%). As can be seen in the 2×2 tables, the Mallett unit found more individuals with a significant aligning prism than the iPad (Tables 3 and 4).

The null hypothesis for the Wilcoxon signed rank test was as follows: ''the median of differences between the

Table 3 The proportion of participants with a significant horizontal fixation disparity (FD) on each instrument.

	Significant horizontal FD on Mallett unit	Non-significant horizontal FD on Mallett unit
Significant horizontal FD on iPad	7 (8.75%)	7 (8.75%)
Non-significant horizontal FD on iPad	10 (12.5%)	56 (70%)

Table 4 The proportion of participants with a significant vertical fixation disparity (FD) on each instrument.

	Significant vertical FD on Mallett unit	Non-significant vertical FD on Mallett unit
Significant vertical FD on iPad	0 (0%)	0 (0%)
Non-significant vertical FD on iPad	2 (2.5%)	78 (97.5%)

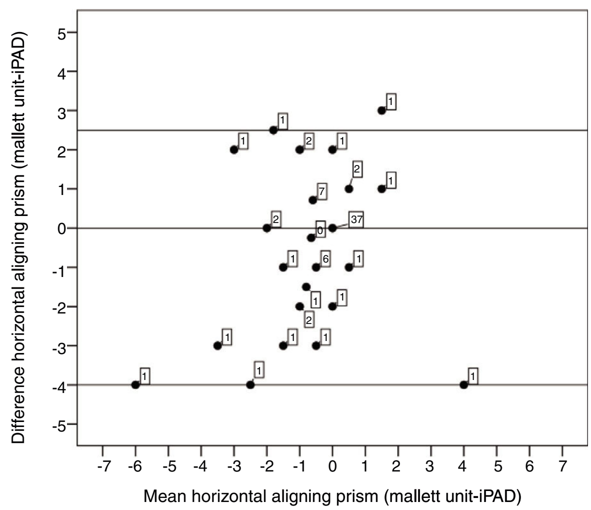

Figure 3 Bland and Altman plot for horizontal aligning prism data. The number of subjects at each data point is represented by the accompanying number.

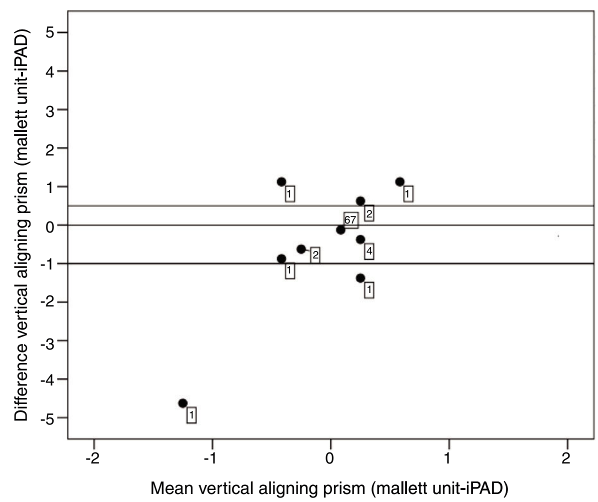

Figure 4 Bland and Altman plot for vertical aligning prism data. The number of subjects at each data point is represented by the accompanying number.

Mallett unit total horizontal/vertical prism and iPad total horizontal/vertical prism equals zero''. The test yielded a significance of $p = 0.357$ and $p = 0.236$, for horizontal and vertical fixation disparity respectively. With the threshold set at $p = 0.05$, in both cases the null hypothesis was retained, and no statistical significance was found for the differences in the data obtained from the Mallett unit and iPad.

The difference in aligning prism was plotted against the average aligning prism for the two instruments for each participant, both for horizontal and vertical data sets (Figs. 3 and 4 respectively). Each plot displays the mean and 95% limits of agreement. Considering the non-parametric nature of these results a modified version of this plot was used as recommended by Bland and Altman.[14] In this, the usual diagram is plotted but reference lines are also included within which 95% of the data sets lie, as opposed to being calculated from standard deviations.

The largest difference in aligning prism between the Mallett unit and iPad for an individual participant was 14 prism dioptres horizontally (mean difference = 0 prism dioptres, median = 0 prism dioptres); this was not included in Fig. 3 but was included in all other calculations. The largest difference in vertical aligning prism findings between the Mallett unit and iPad for an individual participant was 4 prism dioptres (mean difference = 0.1 prism dioptres base down, median = 0 prism dioptres). All data sets were included in the graph.

For the horizontal aligning prism results the median was 0.0 and 95% limits of agreement were from + 2.5 to −4.0. For vertical aligning prism results the median was 0.0 and the limits of agreement were from + 0.5 to −1.0.

For both the horizontal and vertical fixation disparity data plots, most data points are found at the origin. The data are more scattered however for the horizontal fixation disparity results. For vertical fixation disparity results the data is more evenly distributed about the origin.

43.75% of participants reported no NPA viewing the Nonius markers on both instruments, regardless of a fixation disparity being present (Table S1). Of the 45 participants who did report NPA, this was either flashing, blurring or dimming of the markers, and this occurred on both or just one of the instruments. 17 participants reported these issues viewing the Nonius markers on both instruments, 18 participants had NPA only on the Mallett unit, and 10 participants only had NPA on the iPad, in all cases with or without a fixation disparity. However, upon close inspection of the data, these NPA were not found to be correlated with the presence of a fixation disparity nor the instrument used.

Discussion

The 2 × 2 tables revealed that almost 50% of participants had no fixation disparity on both instruments, as is expected for the majority of the population.[9] There was however more agreement between the instruments on participants having a horizontal fixation disparity than for those with a vertical fixation disparity, although the exact aligning prism values obviously differed. In terms of the magnitude of aligning prism however, the instruments agreed more for vertical measures than for horizontal measures; this can be seen on the Bland and Altman plots with the 95% limits of agreement being much narrower for the vertical aligning prism plot. This is likely to reflect the fact that prevalence and range of vertical aligning prism is lower than for horizontal readings.

It is interesting to see the range of results produced by each instrument. The iPad yielded a larger range horizontally, but the Mallett unit did vertically. The reason for this difference is unclear but as will be discussed, both instruments did not agree as well on horizontal aligning prism magnitudes as they did with vertical ones.

The Wilcoxon signed rank test revealed that the difference in aligning prism value yielded by each test was statistically insignificant. This is likely to be strongly influenced by the large number of participants who had exact agreement in results, because they had zero aligning prism on both tests. Therefore, although no statistical significance was found, the differences found in the non-zero values of aligning prism on each instrument are likely to be clinically significant. Clinically significant was defined as a difference in the aligning prism obtained from each instrument $\geq 1\Delta$ for pre-presbyopes and $\geq 2\Delta$ in presbyopes; this is based on the findings of Jenkins et al.[9] who found these degrees of aligning prism to differentiate symptomatic from asymptomatic participants.

In terms of the 2 × 2 tables of the proportion of participants found on each instrument with ''significant'' degrees of aligning prism, most participants were classified as normal (≥70%). Taking into consideration the proportion of participants where the instruments disagreed (21.25% horizontally and 2.5% vertically) we return to the issue of whether it would be acceptable clinically to use these instruments interchangeably as one instrument would indicate the need for prism or a larger degree of prism whereas the other would not. This is further supported by the spread of data on the Bland and Altman plots; looking at the 95% limits of agreement, the horizontal aligning prism could differ by up to 4 prism dioptres, and vertical prism by up to 1 prism dioptre, which in a clinical environment is significant and unacceptable. If the normal values for aligning prism for the Mallett unit[9] are applied to the iPad then this could potentially lead to a very large difference in the prism prescribed, resulting in possible non-tolerance of spectacles.

It is interesting to speculate on why the two tests give different results. Ukwade[15] investigated the effects of varying the Nonius strip separation and size, and the presence of either a central/peripheral/central and peripheral fusion target on fixation disparity. Two experiments were conducted; in the first (a) the Nonius marker length was varied; in the second (b) the Nonius marker separation was varied. It was found that Nonius markers with a length subtending more than 1 degree resulted in no variation of the results. Peripheral fusion locks and larger marker separations were shown to reduce repeatability of subject responses. Ukwade concluded that the most repeatable results were obtained with the presence of a central fusion lock and Nonius marker separation of less than 20 min or arc, which is achieved by neither the Mallett unit nor the iPad test.

Wildsoet and Cameron[16] investigated the effect of the presence of a central fusion lock on the degree of fixation disparity. Each participant was tested first using the Sheedy Disparometer (a fixation disparity test commonly used in North America which lacks a central lock), and a second time with an added central fusion target. The introduction of a central fusion lock significantly altered the results and generally stabilised the Nonius strips. The effect of adding a central fusion lock on a Sheedy Disparometer was also investigated by Brautaset and Jennings,[17] but this time looking closely at the influence of a central fusion lock on the relationship between subjective and objective measurements. The researchers concluded, with investigations conducted on only five subjects, that the presence of a central fusion lock improved correlation between subjective and objective findings, as well as a reduction in size of the measurable fixation disparity.

Pickwell et al.[18] compared results obtained from the Sheedy Disparometer and the Mallett unit, the key difference in these being the presence of a central fusion lock only with the Mallett unit. Two groups were used in this study; subjects with and without experience of prism vergence measurements. The results indicated that although the difference in measurements between the two instruments was insignificant in the ''experienced'' group, they were significant in the ''naive'' group. Overall, greater degrees of fixation disparity were measured using the Sheedy Disparometer in comparison to the Mallett Unit.

The work of Fogt and Jones[19] and Shimono et al.[20] suggested that a central fusion lock which was too close to the Nonius markers would result in invalid fixation disparity results, the effect of Nonius bias. A similar study to that of Ukwade[15] was conducted by Jaschinski et al.[21] who investigated the effect of Nonius marker separation, and so the distance of them from the central fusion lock, on the measured fixation disparity. These markers were presented either continuously or as a flash, with differing results for both situations. Results showed that with continuous display of the markers there was no effect of the gap variation, and little correlation could be found with gap size when the markers were flashed.

A recent report found that 65% of Americans suffer eyestrain after prolonged use of digital devices.[22] Köpper et al.[23] found that asthenopic symptoms are more pronounced when viewing screens relative to printed paper. These persisted even when screen luminance was reduced to match that of paper but were eliminated when the inclination angle of the screen was matched to that used with paper. Hayes et al.[24] found that time spent using digital devices and poor ergonomics correlate with eye symptoms. Agarwal et al.[25] concluded that eyestrain correlates strongly with more than 6 hours a day of computer use.

Although Phamonvaechavan[26] found pain and blurred vision symptoms to be worse following iPad use compared to computer use, this was after a continuous 20-min period of using these devices. Recent reviews by Coles-Brennan et al.[27] and Rosenfield[28] noted the multifactorial nature of digital eyestrain (computer vision syndrome) and cited several studies highlighting the association of symptoms with prolonged use of digital devices. Rosenfield[28] concluded that the accommodative and vergence responses to viewing electronic screens was similar to those required for viewing printed text, negating the fact that these could be a contributor to computer vision syndrome. Hue et al.[29] investigated reading speed, accommodative response and ocular symptoms when using a digital screen (Kindle and iPod) versus printed text. Subjects performed a reading task in each condition for 20 min and it was found that the Kindle caused significantly greater symptoms, but the iPod resulted in a larger accommodative lag and reduced reading speed compared to reading from printed text. Considering the accommodative lag, the mean absolute difference between that for the iPod and printed text was small (0.19D) and negligible between the Kindle and printed text (0.01D). In the context of this study, considering the short period for which the participants viewed the iPad screen and that they held this at their comfortable reading position it is unlikely that the digital nature of this device is a contributing factor to the difference in the results found between the two instruments.

We know of no research investigating the influence on fixation disparity tests of the method of dichoptic separation (cross-polarised v red/green), but anaglyph glasses have been criticised as introducing an artefact into binocular vision testing. Vancleef et al.[30] conducted a study to establish whether over-estimation of stereo thresholds on the TNO test was due to differences in global or local stereopsis. It was found that the TNO test over-estimates stereo thresholds by a factor of two, compared with other tests. This discrepancy could not be attributed to the global/local distinction but instead the authors hypothesise that this could be an artefact of the use of anaglyph glasses.

This has also been suggested by Simons and Elhatton[31] who showed that anaglyph glasses introduce an artefact into binocular vision testing, and Larson[32] who found that stereoacuity is reduced by up to 34 seconds of arc with the TNO anaglyph glasses.

It is of course critical that whichever glasses are used do completely dissociate the two eyes with respect to the view of the Nonius markers. The broadband nature of the filter transmission makes this more difficult to achieve when using red/green filters, in comparison to polarised filters. Unintended residual visibility of one or both of the Nonius markers could influence the results obtained.

It is important to also note the difference in the light transmission of the polarised filters versus the red/green filters. The red/green filters have a significantly lower degree of light transmission and create a less natural visual environment in comparison to the polarised filters, which could negatively impact binocularity and lead to increased dissociation. Grolman[33] suggested that a reduction in illumination would cause an increase in fixation disparity due to reduced visibility of the peripheral fusion lock. Wildsoet and Cameron[16] investigated the effects of varying illumination and the presence of a central fusion lock on the degree of fixation disparity. Their results suggested that varying illumination levels caused no significant change in any parameter. Pickwell et al.[13] found that low illumination increases fixation disparity. Attention should also be drawn to the unmatched light transmission of the red and green filters individually; although not significantly different it could also potentially lead to binocular dissociation in particularly sensitive individuals.

The near Mallett fixation disparity test has been shown to be a useful tool in clinical practice. It can be used to indicate whether a heterophoria is likely to be associated with symptoms, and, the required prism or sphere to be prescribed, if this is the management option pursued. Yekta and Pickwell[7] found a weak association between dissociated heterophoria and fixation disparity, and that symptomatic participants required a greater degree of aligning prism. Karania and Evans[8] showed an association between severity of symptoms and magnitude of aligning prism with the Mallett unit. It should be noted that research supporting the use of the near Mallett fixation disparity unit uses the test as recommended by Mallett,[6] to as closely as possible simulate normal viewing conditions. If the test is used in a way that creates a dissociative environment (e.g., with the patient adjusting rotary prisms[34]), this is likely to produce anomalous results.

The present research does not indicate which of the two instruments studied is most appropriate for clinical practice as the difference in results between the Mallett unit and iPad test is clinically significant. Further research is required to identify which test best predicts symptoms and which test identifies an aligning prism that would alleviate symptoms, although previous research reviewed above supports the value of the near Mallett unit in this regard.

Another issue that is highly relevant to any investigation of agreement, is the repeatability of the measurements. If the test−retest repeatability of one or both of the tests is poor, then there can never be good agreement between them. Alhassan et al.[35] conducted an investigation into the repeatability of fixation disparity instruments. A range of instruments were tested at distance and near, including the Mallett unit and Sheedy Disparometer, on both symptomatic and asymptomatic participants. They found all tests to have good repeatability with the exception of the Sheedy Disparometer, which could be an artefact of its design (lack of a central fusion lock).

Alhassan et al.[35] found their data to have 95% limits of agreement of ± 2.0 for horizontal aligning prism and ± 0.375 for vertical aligning prism at near. These limits of agreement are much narrower than those found in this study showing the Mallett unit to have better test−retest repeatability than the inter-test repeatability found in this research. However, Alhassan et al. appear to have used parametric statistics to assess the repeatability, which is likely to be a source of error owing to the non-parametric distribution of aligning prism. It would be useful for further research to investigate the reproducibility of both techniques using the non-parametric method of Bland and Altman and using the test procedure recommended by Karania and Evans[8] (Figure S1). This is especially important considering the finding in the present research that although the results are not significantly different in a Wilcoxon analysis, Bland and Altman plots show that in some cases the differences between the instruments' results are clinically meaningful.

Interestingly, in this study the Mallett unit revealed more significant aligning prism both horizontally and vertically. The significant inter-instrument variability found in the present research raises two questions that should be addressed in future studies. First, which instrument is best at discriminating symptomatic from asymptomatic participants? Second, which instrument is best at determining the minimum aligning prism that will alleviate symptoms? Very few randomised controlled trials have been conducted which investigate aligning prism. An early double-masked randomised controlled trial[36] showed that the aligning prism prescribed by the Mallett unit was preferred to spectacle lenses without an aligning prism. O'Leary and Evans[37] investigated the effect of an aligning prism versus a control lens on performance of the Wilkins Rate of Reading Test. All eighty participants were selected as having a measurable fixation disparity, and the researchers concluded that exophoric participants with an aligning prism of two prism dioptres or more are likely to have improved visual performance with the aligning prism, even if asymptomatic.

Strengths and limitations

Naïve participants consulting a community optometric practice with a large age range and differing working distances were used in this study which allows its results to be widely applied to the clinical population. The results covered a wide range of aligning prism values, which helps make the results generalisable.

As with any study, limitations are inevitable. The results of this study may not be applicable to those under the age of 16 years. The spectacle/contact lens prescription was not recorded for any of the participants, for simplicity. But, as there were no exclusion criteria based on prescription, the population studied is likely to be typical of the cross-section of patients consulting an optometrist. The centration of the spectacles was not recorded, so it is likely that some participants were experiencing a prismatic effect from their lenses: however, this would be expected to influence the results of each test equally.

The lack of previous research with the iPad instrument made sample size calculations problematic. Although a sample of 80 was obtained, it is possible that the Wilcoxon analysis would have reached statistical significance with a larger sample size. However it is unlikely that this would have changed the clinical interpretation of the results. This is clearly shown in the 2×2 tables which accurately describe the discrepancies between the two techniques, and the precision afforded by the sample size is addressed in the Bland and Altman analysis by the calculation of the 95% limits of agreement.

Conclusion

This study reveals that the conventional Mallett unit and an iPad fixation disparity test produce results that are different, in many cases in a clinically significant way. The instruments differ in the individuals categorised as abnormal and in the magnitude of aligning prism. We recommend that the instruments should not be used interchangeably. Further research is required to determine which instrument best detects symptomatic heterophoria, which is most useful for prism prescribing, and the test–retest repeatability of the instruments using a non-parametric method. Previous research supports the use of the Mallett unit in diagnosing individuals with symptomatic heterophoria,[7,9] and in providing a prismatic prescription that alleviates symptoms[36] and may improve performance.[37–40] There is a diversity of opinion on prism prescribing. However, while some studies indicate the near Mallett unit is useful for prescribing prisms, there is no similar evidence about the validity of the Thomson Vision Toolbox. Considering the present research shows the Thomson test is not interchangeable with the Mallett unit, this raises questions over its clinical utility.

Conflicts of interest

The authors have no conflicts of interest to declare.

Acknowledgements

We would like to express our appreciation to the individuals who took part in this study. Many thanks also to Cole Martin Tregaskis Optometrists for funding the iPad software used, and to Aarons Optometrists Ltd. where the data was collected for this study. This research did not receive any grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.optom.2019.03.002.

References

1. Evans BJ. *Pickwell's Binocular Vision Anomalies*. 5th ed. UK: Butterworth Heinemann; 2007.
2. Rowe FJ. *Clinical Orthoptics*. 3rd ed. Chichester, West Sussex: Hoboken: Wiley; 2012.
3. Ogle KN, Mussey F, De HPA. Fixation disparity and the fusional processes in binocular single vision. *Am J Ophthalmol*. 1949;32:1069–1087.
4. Ogle KN. *Researches in Binocular Vision*. Philadelphia: Saunders; 1950.
5. Ogle KN, Martens TG, Dyer JA. Oculomotor imbalance in binocular vision and fixation.
6. Mallett RFJ. The investigation of heterophoria at near and a new fixation disparity technique. *Optician*. 1964;148: 573–581.
7. Yekta A, Pickwell L. The relationship between heterophoria and fixation disparity. *Clin Exp Optom*. 1986;69:228–231.
8. Karania R, Evans BJW. The Mallett Fixation Disparity Test: influence of test instructions and relationship with symptoms. *Ophthalmic Physiol Optics*. 2006;26:507–522.
9. Jenkins TC, Pickwell LD, Yekta A. Criteria for decompensation in binocular vision. *Ophthalmic Physiol Optics*. 1989;9:121–125.
10. Patel T. *Comparison of the Fixation Disparity Test Parameters on different Near Vision Fixation Disparity Units. BSc [Optometry Thesis]*. London: City University London; 2012.

11. Thomson Software Solutions. Test Chart 2016, http://www.thomson-software-solutions.com/Test Chart 2016/Help/Test Chart 2016.html?Introduction.html Accessed 16.08.17.
12. Evans B, Pickwell D. *Pickwell's Binocular Vision Anomalies: Investigation and Treatments*. 3rd ed. Oxford: Butterworth-Heinemann; 1997.
13. Pickwell LD, Yekta AA, Jenkins TCA. Effect of reading in low illumination on fixation disparity. *Optometry Vision Sci*. 1987;64:513–518.
14. Bland J, Altman D. Measuring agreement in method comparison studies. *Stat Methods Med Res*. 1999;8:135–160.
15. Ukwade MT. Effects of nonius line and fusion lock Parameters on Fixation Disparity. *Optometry Vision Sci*. 2000;77:309–320.
16. Wildsoet CF, Cameron KD. The effect of illumination and foveal fixation lock on clinical fixation disparity measurements with the Sheedy Disparometer. *Ophthalmic Physiol Optics*. 1985;5:171–178.
17. Brautaset RL, Jennings JAM. Measurements of objective and subjective fixation disparity with and without a central fusion stimulus. *Med Sci Monit*. 2006;12:MT1–MT4.
18. Pickwell LD, Gilchrist J, Hesler J. Comparison of associated heterophoria measurements using the Mallett test for near vision and the Sheedy Disparometer. *Ophthalmic Physiol Optics*. 1988;8:19–25.
19. Fogt N, Jones R. Comparison of fixation disparities obtained by objective and subjective methods. *Vision Res*. 1998;38:411–421.
20. Shimono K, Ono H, Saida S, Mapp AP. Methodological caveats for monitoring binocular eye position with nonius stimuli. *Vision Res*. 1998;38:591–600.
21. Jaschinski W, Kloke W.-B., Jainta S, Buchholz J. Horizontal fixation disparity measures with nonius lines. *Optometry Vision Sci*. 2005;82:988–999.
22. The Vision Council. *Eyes Overexposed: The Digital Device Dilemma. Digital Eyestrain Report*; 2016.
23. Köpper M, Mayr S, Buchner A. Reading from computer screen versus reading from paper: does it still make a difference? *Ergonomics*. 2016;59:615–632.
24. Hayes JR, Sheedy JE, Stelmack JA, Heaney CA. Computer use, symptoms, and quality of life. *Optometry Vision Sci*. 2007;84:E738–E755.
25. Agarwal S, Goel D, Sharma A. Evaluation of the factors which contribute to the ocular complaints in computer users. *J Clin Diagn Res*. 2013;7:331–335.
26. Phamonvaechavan P. A comparison between effect of viewing text on computer screen and iPad® on visual symptoms and functions. *Siriraj Med J*. 2017;69:185–189.
27. Coles Brennan C, Sulley A, Young G. Management of digital eye strain. *Clin Exp Optometry*. 2019;102:18–29.
28. Rosenfield M. Computer vision syndrome: a review of ocular causes and potential treatments. *Ophthalmic Physiol Optics*. 2011;31:502–515.
29. Hue JE, Rosenfield M, Saá G. Reading from electronic devices versus hardcopy text. *Work*. 2014;47:303–307.
30. Vancleef K, Read JC, Herbert W, Goodship N, Woodhouse M, Serrano-Pedraza I. Overestimation of stereo thresholds by the TNO stereotest is not due to global stereopsis. *Ophthalmic Physiol Optics*. 2017;37:507–520.
31. Simons K, Elhatton K. Artefacts in fusion and stereopsis testing based on red/green dichoptic image separation. *J Paediatr Ophthalmol Strabismus*. 1994;31:290–297.
32. Larson WL. Effect of TNO red-green glasses on local stereoacuity. *Optometry Vision Sci*. 1988;65:946–950.
33. Grolman B. Binocular refraction—fixation disparity. *Optician*. 1971;162:16–19.
34. Kommerell G, Kromeier M, Scharff F, Bach M. Asthenopia, associated phoria, and self-selected prism. *Strabismus*. 2015;23:51–65.
35. Alhassan M, Hovis JK, Chou RB. Repeatability of associated phoria tests. *Optometry Vision Sci*. 2015;92:900–907.
36. Payne CR, Grisham DJ, Thomas KL. A clinical evaluation of fixation disparity. *Optometry Vision Sci*. 1974;51:88–90.
37. O'Leary CI, Evans BJW. Double-masked randomised placebo-controlled trial of the effect of prismatic corrections on rate of reading and the relationship with symptoms. *Ophthalmic Physiol Optics*. 2006;26:555–565.
38. Jenkins TC, Abd-Manan F, Pardhan S. Fixation disparity and near visual acuity. *Ophthalmic Physiol Optics*. 1995;15:53–58.
39. Jenkins TC, Abd MF, Pardhan S. The effect of artificially created fixation disparity on near visual acuity. *Optometry Vision Sci*. 1994;71:647–648.
40. Jenkins TC, Abd-Manan F, Pardhan S, Murgatroyd RN. Effect of fixation disparity on distance binocular visual acuity. *Ophthalmic Physiol Optics*. 1994;14:129–131.