Susceptibility to Visual Discomfort of 3-D Displays by Visual Performance Measures

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Abstract—People with some signs of binocular dysfunctioning can be susceptible to visual complaints associated with viewing stereoscopic content at large viewing distances. Two performance measurements enabled to distinguish people by their binocular status (BS) in previous research: the ratio of performance of the Wilkins rate of reading test (WRRT) between 2-D and 3-D, and the vergence facility. In an experiment, first, an extensive optometric screening was carried out to differentiate visually asymptomatic young adults with good BS (GBS) (N = 27) from those with a moderate BS (MBS) (N = 6). Second, participants had to perform the WRRT at short viewing distance followed by a questionnaire under different screen disparity settings. The results reveal that the ratio of the WRRT between 0 and −1.5 screen disparity is an appropriate indicator of participants with MBS in comparison with participants with GBS. In addition, the results show that 0.75° of screen disparity is already problematic for people with MBS. We conclude that the WRRT-ratio has potential as a BS test in consumer applications to provide individual settings for comfortable screen disparities based on viewers’ BS.

Index Terms—3-D displays, optometric measurement, reading speed, stereo vision, visual discomfort, visual performance.

I. INTRODUCTION

STEREOSCOPIC movies boost the viewing experience by rendering content in front of or behind the display plane, yet numerous studies have reported an association with visual complaints [1]–[10]. The effects of stereoscopic content on visual discomfort vary among people since visual functions differ [2], [10]–[12]. When constructing guidelines for the creation and viewing of 3-D content it is important to take account of the range of visual functions that are likely to be encountered in viewers.

The visual system of the majority of people may be characterized as normal, yet there still are differences in performance between them. There is a paucity of epidemiological data on the prevalence of binocular vision anomalies, but some degree of binocular anomaly affects approximately 10–20% of patients consulting community optometrists [13], with the wide range of figures in this review reflecting inconsistencies in the underlying literature [14]–[19]. Severe binocular anomalies such as strabismus (squint) and amblyopia (lazy eye) typically prevent stereopsis. So-called non-strabismic binocular anomalies permit stereopsis, but predispose the patient to asthenopia (eyestrain and headaches). These visual complaints may not be present in normal viewing situations, but may occur or become more severe in unnatural viewing situations, such as viewing stereoscopic content.

In the case of stereoscopic near work, visual complaints can solely result from accommodative dysfunctions. These accommodative dysfunctions affect up to 16% of patients consulting community optometrists [17], [18], though this prevalence is much higher (60%) among patients receiving treatment for binocular anomalies [18], [19]. The symptoms of both binocular and accommodative anomalies are diverse and nonspecific, which complicates the relationship between people’s binocular functioning and the occurrence of visual complaints for stereoscopic near work. Clinically, the diagnosis of these conditions is based on several subjective and objective methods, in combination with the practitioner’s knowledge and experience. In other words, the identification of people with poorer accommodative and binocular visual functioning has hitherto involved extensive optometric testing. If participants who are prone to visual complaints associated with stereoscopic viewing as a consequence of their binocular functioning can be detected by a simple test of reading performance then this has two important implications. First, such a test could be used in perceptual research, perhaps complementing the information provided by stereo acuity and visual acuity tests. Second, this test could be a useful tool in consumer applications to individually set comfortable screen disparities based on viewers’ binocular status (BS).
II. BACKGROUND

A. Binocular Functioning

To obtain clear, binocular single vision, the visual system maintains accommodation and convergence that are appropriate for the viewing distance. Vergence can be defined as the movement of the eyes in opposite directions to maintain fixation on an object that is moving in depth. The vergence system is primarily retinal disparity-driven and resolves mismatches in the fusion system [18], [20]. In most cases, the vergence system compensates for binocular anomalies such as heterophoria (the tendency of the eyes to misalign when they are dissociated) or fixation disparity (the minimum angular measure of misalignment of the visual axes of the eyes). People with inadequate fusion or an excessive heterophoria may require more effort to maintain fusion. This may lead to visual complaints when viewing stereoscopic content [13], [21]–[23]. In this case, the heterophoria is described as decompensated and may be associated with clinical signs such as fixation disparity [15], [24], for a review see [13].

Accommodation concerns the alteration of the crystalline lens to obtain and maintain the object of interest with the highest attainable resolution focused on the fovea. The accommodation system is primarily driven by retinal blur and can compensate for small errors in specific accommodative dysfunctions [7], [9], [18], [20]. In unnatural or stressful viewing situations, such as stereoscopic near work, people with smaller tolerance in their accommodative functioning can expend so much effort that visual complaints may arise [17], [21], [22], [25]–[28].

The literature described above generally supports the need for clinically testing people before they participate in stereoscopic perception experiments, and ideally before they view stereoscopic full-feature movies or participate in other simulated 3-D viewing environments. This is because simulated 3-D content creates artificial viewing conditions, most notably by creating a different stimulus to vergence and accommodation [1], [9].

For diagnosing binocular dysfunctions no single test is 100% effective or objective [29]. In view of this, Evans [13], [30] constructed an algorithm (described in Section III-B) for diagnosing decompensated heterophoria that computes a score representative of a person’s BS. This algorithm has been used in previous research to provide an index of the BS of heterophoric subjects, that is the degree to which their heterophoria is compensated [31]. In a recent study, this algorithm was applied to discriminate people with normal binocular functioning from those with moderate BS (MBS), and consequently, with a higher susceptibility to visual complaints associated with viewing stereoscopic displays at a large viewing distance [10]. Seven of the 39 participants (18%) were identified as people with a MBS. After short-term stressful stereoscopic reading tasks at a viewing distance of three meters these seven participants revealed objective signs of visual fatigue and indicated more visual discomfort in contrast to those participants with a good BS (GBS).

In case of stereoscopic near work, participants should be screened for both binocular and accommodative functioning.

Dysfunctions in either systems can cause similar, nonspecific, visual complaints including blurred, double, or distorted vision, difficulty in changing focus, headache, achy eyes, sore eyes, and irritated eyes [17], [18], [28], [29]. Hence, it is not that straightforward to determine whether a symptom associated with stereoscopic near work is attributable to a binocular vision anomaly, an accommodative dysfunction, to both, or maybe even another condition, e.g., dry eyes.

B. Reading Performance

Reading difficulties are a common symptom in people with visual dysfunctions [32]. It is widely reported that visual defects (e.g., visual acuity, fixation disparity, fusion, accommodation, vergence, and visual stress) can impair reading ability and induce visual complaints when reading [32]–[36]. For people with accommodative dysfunctions test will be out of focus, which may impair reading performance since blur impedes resolving detail. For people with binocular dysfunctions, text may appear doubled, blurred, or distorted due to vergence errors while making saccades or making return sweeps at the end of the line [13], [34].

The extent of these reading impairments can be properly assessed with the Wilkins rate of reading test (WRRT) [36]–[39]. The WRRT will be discussed in more detail in Section III-D. It was originally developed to assess symptoms that are alleviated by using colored filters of a specific tint while reading [37]. Jeanes et al. [34] reported that children who benefit from using colored filters, showed an improvement in performance of 8% with the WRRT. O’Leary and Evans [36] found that correcting decompensated heterophoria improved performance at the WRRT. Lambooij et al. [10] revealed that people with a MBS classified by Evans’ algorithm [30] showed a significantly higher ratio in performance of the WRRT between 2-D and 3-D than people with GBS. In the rest of this paper, the WRRT-ratio is used to describe the ratio calculated from (number of words read in 2-D)/(number of words read in 3-D). Participants with a MBS had on average a WRRT-ratio of 1.8, whereas participants with a GBS had on average a WRRT-ratio of 1.5. In other words, the adverse effect of screen disparity on reading performance was larger for people with a MBS than for people with a GBS.

C. Facility Measurement

An indication of a normal visual system is proper adaptation and sufficient facility to respond to alterations in the viewing environment [23]. Vergence facility is the ability of the fisional vergence system to respond efficiently and accurately to changing demands over time [40]. Vergence facility testing improves the diagnosis of binocular dysfunctions [40] and is an indicator of readiness for binocular visual tasks [17], [41]. The research of Lambooij et al. [10] revealed that participants with a MBS, who experienced more visual complaints associated with stereoscopic reading tasks, had a lower vergence facility than participants with a GBS. Analogously, accommodation facility is the ability of the accommodative visual system to respond efficiently and accurately to changing demands over time [42]. It is used as an indicator of readiness for near
vision tasks [17], [42]. Testing accommodation facility under binocular test conditions provides: 1) a direct evaluation of the dynamics of accommodative response similar to under monocular test conditions, and 2) information about the coupling between accommodation and vergence [13], [40], [42]. As such it is also referred to as interactive facility and seems appropriate for stereoscopic near work.

D. Hypotheses

The current research aims: 1) to provide further data on the proportion of people who are susceptible to such visual complaints, and 2) to construct relatively simple performance measurements that can be used to identify a subgroup of participants who might be more susceptible to visual complaints associated with stereoscopic displays at shorter viewing distance.

As stated, Lambooij et al. [10] revealed that susceptibility to visual complaints associated with modern stereoscopic displays can be detected by relatively simple visual performance measures (i.e., reading performance and vergence facility measurement). Since a relatively large viewing distance (3 m) was used in that research, the current research is focused on stereoscopic near work. This may complicate the analysis of the relationship between people’s BS and the occurrence of visual discomfort as a consequence of screen disparity, accommodative dysfunctions might have a perceptual impact as well. In addition, Lambooij et al. [10] used only two screen disparities: zero and 1.5° crossed disparity. To obtain a relationship between visual performance and visual discomfort as a consequence of screen disparity, the current research incorporates more screen disparities.

Participants with normal visual functioning are categorized via an extensive optometric screening into two subgroups: one with a GBS and one with a MBS. It is noteworthy that the original aim was to construct a subgroup of participants with accommodative dysfunctions as well, yet all participants appeared to have proper accommodative status. Three relatively simple indicators are evaluated in terms of their ability to confirm this distinction in subgroups: the WRRT-ratio, the vergence facility, and the accommodative facility.

The former two showed potential to categorize people based on their BS, which determined their susceptibility to visual discomfort associated with viewing stereoscopic displays for a large viewing distance [10]. The latter is incorporated since accommodative dysfunctions may also impact the ability to comfortably view (stereoscopic) content for close viewing distances. The facility measurements are two tests that are not included in Evans’ algorithm and are thought to be most relevant as potential predictors of problems when viewing 3-D displays.

The first hypothesis states that the WRRT-ratio is effective to distinguish people that are more susceptible to visual complaints associated with stereoscopic displays for close viewing distances. The second hypothesis states that vergence facility measured at large viewing distances distinguishes people by their susceptibility to visual complaints associated with stereoscopic near work. The third hypothesis states that for near vision, accommodation facility is a useful indicator to differentiate people’s susceptibility to visual complaints associated with stereoscopic displays.

III. EXPERIMENTAL SET-UP

A. Design

The experimental design consisted of two parts: 1) an optometric screening, and 2) the performance of the WRRT for close viewing distance. The optometric screening included accommodation and vergence facility measurements and facilitated categorization of participants based on their BS: GBS (N = 27) and MBS (N = 6). Neither the participants nor the experimenter knew to which subgroup a participant belonged during the experiment.

In the second part, the WRRT was performed via a Wheatstone viewer under five screen disparity settings (disparity): 1.5, 0.75, 0, −0.75, and −1.5 degrees, where a “+” sign indicates crossed screen disparity. Different WRRTs were assigned randomly to the five screen disparity settings of which the order was randomized across participants. After each WRRT, the subjective visual discomfort was evaluated with a questionnaire containing 15 subjective items (Item). The entire experiment (screening part and experimental parts) was scheduled on one day.

B. Screening of Participants

An extensive optometric screening was carried out on 33 naïve visually asymptomatic participants of age range 18–36 years. This screening was performed for two reasons: 1) to exclude participants with eye diseases or severe binocular abnormalities, such as partial (stereo) blindness, large refractive errors (> 0.50 diopter (DI)), strabismus, and amblyopia, and 2) to differentiate participants in subgroups based on their visual functioning. Subgroups were assembled based on the optometric screening carried out at near vision distances (40–70 cm). All optometric indicators with their exclusion criteria are described in detail in our previous papers [8], [10]. In this paper, only those indicators used to construct the subgroups are discussed.

The categorization of participants based on their BS was established with an optometric algorithm described by Evans [13], [30]. The algorithm can be carried out in two stages: an abbreviated version to rapidly classify normal subjects as such (based on six test results; items 1–6 in Table I) and a more detailed version (which is recommended especially for patients who do not achieve good results on the first six tests) in which four further tests are completed (items 7–10 in Table I). The full version (all ten tests) was used in the present research. This full algorithm calculates the sum of ten scores each of which is the result of a single optometric indicator of decompensated heterophoria (including binocular instability), yet none of which individually is diagnostic of BS by itself [8]. The total algorithm score ranges from 0 to 16; a score of 0–5 is normal and 6 or more abnormal [13], [30]. In this paper, scores of 0–5 inclusive were classified as GBS (27 participants) and 6 or higher as MBS (six participants). The term MBS is used rather than a stronger term (e.g., pathological binocular status)
in recognition of the fact that people with strabismus were excluded from the research.

The algorithm and scoring system are based on a review of the literature [13], [30] and clinical experience using prototypes of the algorithm in the Institute of Optometry clinics over a number of years. The algorithm and scoring system was first described in 1997 [30] and also (unchanged) in subsequent publications [13], [43]–[45]. The published algorithm and scoring system has also been used in previous research as a measure of the degree to which heterophoria is compensated [31] and the decision was therefore made to use the same scoring system and definitions of normal/abnormal as those previously used.

To detect the symptoms that are suggestive of binocular dysfunctions (the first indicator in the algorithm), the convergence insufficiency symptom survey (CISS) was used that incorporates general asthenopic items [10], [21], [46]. Since the CISS questionnaire also incorporates items that relate to reading tasks specifically, it was also used in the actual experiment.

For the objective indicators, a short explanation is given here, though the authors would like to refer to Evans [13] for a more extended description. The cover test assesses ocular alignment (e.g., heterophoria) by covering each eye in turn. Fixation disparity is an angular measure of small misalignments of the visual axes of the eyes, which, if measured with a central fusion lock, provides a more accurate indication of the objective eye position than without a central fusion lock [47]. Aligning prism measures the minimum power of prism that corrects the fixation disparity [15], [24], [48]–[50]. Foveal suppression refers to a very small suppression area that occurs in the foveal region. Convergent and divergent fusional ranges indicate the amount of convergence and divergence, respectively, that can be induced before fusion is compromised. They are commonly characterized with prism loads at which binocular single vision becomes blurred (blur point), is lost (break point), and recovers again (recovery point). The fusion amplitude describes the amplitude between corresponding convergent and divergent fusion blur points. Percival’s and Sheard’s criteria refer to a fusion range that still allows comfortable fusion [51]. Percival’s criterion is defined as the middle third of the “zone of clear, single binocular vision.” This zone can be determined by measuring the blur points of fusion amplitude, i.e., the points at which clear vision is lost. In contrast to Percival’s criterion, Sheard’s criterion takes account of the heterophoria; it states that the opposing blur point should be at least twice the degree of the heterophoria [52], [53].

For the detection of accommodative dysfunctions, suggestions have been made about which accommodation indicators should be included in an optometric screening [17]. An objective protocol of diagnosis to clearly distinguish the subgroup with poor accommodative status, however, is not available to our knowledge. Table II lists the accommodative indicators used in the screening. The accommodation amplitude refers to the shortest distance on which the eyes can monocularly focus. Relative accommodation refers to the maximum amount by which the accommodation can change for a given degree of vergence measured in diopters, which can be positive or negative. In other words, this is the amount by which accommodation can be increased or relaxed, in response to negative or positive lenses respectively, before blur arises while keeping vergence constant. The accommodation response refers to the focus control of the eye, i.e., the accuracy of the accommodation in direction and size. Accommodation facility, which has been explained in detail, is the rate (in cycles per minute) at which the accommodation can be changed to maintain clear vision through alternating opposing lenses. None of the participants had deviating values from the norm for more than one of these indicators, which makes it difficult to create an accommodative subgroup. Table II lists the mean and standard deviation of all accommodative indicator values for the MBS and GBS subgroup and the normal values [13].

The last part of the screening concerned the measurement of the vergence facility. Vergence facility is the rate (in cycles per minute) at which vergence can be changed so that an object is properly fused through alternating base-in and base-out prisms. To prevent subjects requiring a high degree of accommodation, measurement of the vergence facility was performed at a viewing distance of 2.5 m. The commonly used prism combination to test vergence facility, i.e., 12 base out/3 base in, was used in this experiment [40].

C. Equipment

The work unit that was used for the optometric measurements included a control console, an examination chair, a double sliding instrument table, a projector column, and a phoropter. The phoropter contained prisms and lenses to evaluate the visual functions described in the screening. An American Optical projector was used to measure the visual acuity. The Mallett Near Vision Unit (IOO Sales Ltd. London, U.K.) was used to facilitate the measurements of the visual functionality of the participants during screening for near viewing. The Mallett Near Vision Unit is shown in Fig. 1.

To display the stimuli, a screenscope (mirror stereoscope) was used to direct the left-eye and right-eye image of a side-by-side displayed stereo pair to the appropriate eyes as depicted in Fig. 2. This system is location multiplexed thus eliminating crosstalk. It has a viewing distance of 0.40 m.

D. Stimuli

The stimuli in the experiment were five different passages of the WRRT [37] that were randomly assigned to conditions. The WRRT consists of a meaningless passage of seemingly random words: ten lines with the same 15 words distributed randomly on each line (“you for the and not see my play come is look dog cat to up”) that participants are asked to read “out loud” as rapidly and accurately as possible for 60 s. Since common simple words are used, poor readers can perform the task. The text is independent of any syntactic and semantic constraints because participants do not know which word comes next.

This requires them to remain focused on the text. Another consequence of its meaningless content is that readers do not have a sense of failure when making errors. Fig. 3 depicts a
screen shot of a stimulus. Only the text was presented with stereoscopic depth, whereas the frame with the circles was presented at zero disparity. The frame was added around the screen shot of a stimulus. Only the text was presented with stereoscopic depth, whereas the frame with the circles was presented at zero disparity. The frame was added around the

TABLE I
Algorithm Proposed by Evans [30] Applied to Differentiate Participants with Respect to Their Binocular Status Based on Objective and Subjective Optometric Indicators [13], [30]

<table>
<thead>
<tr>
<th>No.</th>
<th>Indicators</th>
<th>Sign or Symptom</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Symptomatic heterophoria</td>
<td>One or more of the questionnaire symptoms (if so, +3 or +2 or +1 if borderline)</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Cover test</td>
<td>Heterophoria detected</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Positive relative accommodation (MEM-retinoscopy)</td>
<td>Presence of rapid and smooth recovery (if so, +2 or +1 if borderline)</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Fixation disparity with fusion lock</td>
<td>Aligning prism (Mallet): &gt;1 PD patients under 40 or &gt;2 PD patients over 40</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Fixation disparity with fusion lock</td>
<td>Aligning prism (Mallet): unstable</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Forehead suppression</td>
<td>Forehead suppression (Mallet): &gt;3 arcmin</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>Sheard’s criterion</td>
<td>Failed</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>Pecival’s criterion</td>
<td>Failed</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>Dissociated heterophoria</td>
<td>Unstable (if range &gt; 4 PD)</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>Fusion amplitude</td>
<td>&lt;20 PD</td>
<td>1</td>
</tr>
</tbody>
</table>

PD: prism diopter.

TABLE II
Mean Values and Standard Deviations of Accommodation Indicators for Participants with GBS and MBS, as Well as the Corresponding Normal Values

<table>
<thead>
<tr>
<th>Indicators</th>
<th>GBS Mean ± STD</th>
<th>MBS Mean ± STD</th>
<th>Norm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accommodation amplitude (binocular push up test)</td>
<td>9.20 ± 1.61</td>
<td>9.94 ± 0.86</td>
<td>15 ± 0.25 (age)</td>
</tr>
<tr>
<td>Negative relative accommodation</td>
<td>2.44 ± 0.50</td>
<td>2.38 ± 0.85</td>
<td>2.60 ± 0.50</td>
</tr>
<tr>
<td>Positive relative accommodation</td>
<td>2.50 ± 1.11</td>
<td>2.13 ± 0.95</td>
<td>2.37 ± 1.12</td>
</tr>
<tr>
<td>Accommodation response (MEM-retinoscopy)</td>
<td>0.48 ± 0.37</td>
<td>0.67 ± 0.26</td>
<td>0.35 ± 0.35</td>
</tr>
<tr>
<td>Accommodation facility (± 3-D lenses)</td>
<td>14.07 ± 4.44</td>
<td>13.80 ± 5.14</td>
<td>8 ± 0</td>
</tr>
</tbody>
</table>

*a Units are in diopters except accommodation facility that is expressed in number of cycles per minute.

*bMEM abbreviates monocular estimation method.

*cReference [34].

The CISS questionnaire included the following items: discomfort, loss of concentration, double vision, sleepiness, sharpness, exhaustion, appearance of moving words, slower reading, losing position in text, trouble remembering words, re-reading words, headache, pain in the eyes, strain in the eyes, and irritated eyes [46]. Participants were asked to assess the items on a scale labeled with the adjective terms: never/infrequently/sometimes/fairly often/always.

F. Procedure
Participants were provided with an informed consent form containing information about the screening and the experiment, such as the general procedure and the possible occurrence of visual discomfort. After signing the informed consent, they proceeded with the optometric screening, which required about 25 min to complete. They received a brief instruction about the specific course of the experiment that incorporated a version of the WRRT to familiarize participants with the specific reading task. All questions concerning the procedure of the experiment were answered, after which the experiment started.

Participants had to properly rest their head against the screenscope in order to maintain the appropriate viewing distance, and to obtain a clear and single image. The initial setting of the stimulus was always with zero screen disparity, yet participants were able to increase the screen disparity stepwise by pressing keypad number 2 (up arrow). Except in the 2-D condition, depending on the condition of the stimulus the WRRT changed in stereoscopic depth: either in crossed or uncrossed disparity. If participants had trouble fusing the stimuli, keypad number 2 (down arrow) could be used to decrease the screen disparity. This stepwise altering of the screen disparity to set any of the five screen disparities (−1.5, −0.75, 0, 0.75, and 1.5 degrees) was included since previous research revealed that not all participants were able to fuse 1.5° of screen disparity in a single step [10]. Hence, participants could increase the screen disparity to the value that belonged to that condition. Once the appropriate screen disparity was set, the participants were asked to read the words “out loud.”
Fig. 1. Mallett near vision unit on which the polarized nonius lines were aligned by using rotary prisms while the subject viewed the small OXO test figure (the instrument is normally internally illuminated). Test instructions followed guidelines of [15].

Fig. 2. Principle of the screenscope, the stereoscopic system used in the experiment to direct the left-eye and right-eye image of a side-by-side displayed stereo pair to the appropriate eyes. The viewing distance (A+B+C) was 0.40 m.

as rapidly as possible for 60 s. It was emphasized that the text needed to be in focus (sharp) and single. Each reading task was followed by the CISS questionnaire and a rest period of approximately 2 min to relax the eyes. The participants were instructed that each time the CISS questionnaire was carried out their responses should relate to symptoms during the experimental condition that had just taken place. This entire procedure was performed five times (i.e., for five different disparity conditions) with the conditions randomized across participants. The experimental session required about 20 min.

IV. RESULTS

As explained in Section III-B, two subgroups were identified based on their visual functioning: participants with a good binocular status (N = 27) and participants with a moderate binocular status (N = 6), referred to as GBS and MBS, respectively.

A. Subjective Results

Most of the CISS items yielded an averaged visual discomfort score around two, referring to moderate levels of visual discomfort. Not all items were affected similarly by changes in disparity or experienced equally by the two subgroups of participants. A principal component analysis (PCA) was performed to find intrinsic correlations between the 15 items and to reveal if certain items shared similar underlying attributes of visual discomfort [56]. The PCA was combined with a non-orthogonal rotation method (Oblimin) to minimize the number of items with high factor loadings on more than one factor. The resulting PCA revealed two underlying factors that explained 39% and 19% of the variance of the data. Factor 1 received meaningful factor loadings (> 0.50 [56]) of the items moving words, slower reading, sharpness, loss of position in text, rereading words, and double vision and relates to misperception of text. Factor 2 consisted of exhaustion, headache, pain, strain, and discomfort and relates to asthenopia. Reliability testing revealed Cronbach’s alphas of 0.84 and 0.75 for factors 1 and 2, respectively (a Cronbach’s alpha of > 0.70 is considered acceptable [56]).

The items concentration problems, sleepiness, irritated eyes, and remembering words received a low factor loading on both factors 1 and 2. Based on the reliability analysis it was decided to exclude these items from further analysis. For each participant, a factor score was calculated for each factor in each condition, i.e., the score given by the participant on each questionnaire item was weighted with the factor loading of that item, and then summed over all items of the factor [50]. An analysis of variance (ANOVA) with BS and disparity as independent variables revealed that factor 1 was significantly affected by disparity (F(1, 155) = 2.553, p < 0.05). Factor 2 was significantly affected by BS (F(1, 155) = 14.810, p < 0.001), disparity (F(4, 155) = 4.747, p < 0.05) and the interaction between BS and disparity (F(4, 155) = 2.780, p < 0.05). The results are depicted in Fig. 4 for factors 1 (upper panel) and 2 (lower panel). It is noteworthy that there is a significant increase in factor 2 for the MBS group when a disparity of 0.75 degrees was reached.
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Fig. 4. Mean visual comfort factor scores of the two sets of questionnaire items of (a) factor 1 and (b) factor 2. The x-axes represent the different screen disparities, the y-axes the average factor scores, and the different lines in the lower panel the two subgroups.

B. Accommodation and Vergence Facility

Fig. 5 depicts the average measurement results of the accommodation facility (upper panel) and vergence facility (lower panel) per BS subgroup including the 95% confidence intervals and norm values.

A multivariate ANOVA revealed no statistically or clinically significant differences between the two different BS subgroups in terms of their accommodation facility ($p = 0.337$) and vergence facility ($p = 0.202$).

C. WRRT Performance

The upper panel of Fig. 6 depicts the number of words read as a function of disparity for both subgroups, whereas the lower panel of Fig. 6 depicts the ratio of words read in 2-D compared to 3-D as a function of disparity for both subgroups.

Concerning the data illustrated in the upper panel of Fig. 6, an ANOVA revealed that the performance at the WRRT (i.e., number of words read) did not significantly differ between levels of disparity ($F(1, 155) = 2.070, p = 0.087$) or between the BS subgroups ($F(1, 155) = 1.211, p = 0.273$). There is a clear effect visible, however, of disparity on the performance of the WRRT for the MBS subgroup, but this was not significant. It is plausible that this is due to the small number of participants in this group ($N = 6$). The analysis of the ratio of the number of words read between 2-D and 3-D, i.e., WRRT-ratio in the lower panel of Fig. 6, revealed that BS ($F(1, 124) = 23.805, p < 0.001$) and disparity ($F(3, 124) = 3.751, p < 0.05$) had a significant effect on this ratio.

A reverse analysis should reveal if this WRRT-ratio can be used to predict the BS, i.e., distinguish the MBS subgroup from the GBS group. For the reverse analysis, only the WRRT-ratio of the 1.5 crossed screen disparity was used, i.e., $-1.5^\circ$. It revealed a large difference in WRRT-ratio between both subgroups and small variances per subgroup, whereas the variance of the WRRT-ratio in the uncrossed screen disparity was much higher for both subgroups. Hence, the crossed screen disparity condition appeared most appropriate. Since the implementation of a tool should be as simple as possible, a cut-off value of 1.25 in the WRRT-ratio was chosen which is the mean plus one STD of all participants, i.e., $1.10 + 0.15$. Table III depicts the distinction accomplished by the WRRT-ratio when applying this limit.

The discriminating performance of the WRRT-ratio criterion can be reflected by the sensitivity index $d'$ [57]. The sensitivity index is defined as the standardized distance between the...
means of both subgroups and is calculated by the difference between the normal deviates of the hit rates and false positives.

Calculation of $d'$ entails the assumption that both subgroups have stochastic responses that are normally distributed and that all quadrants of the contingency matrix have equal impacts. The criterion of the WRRT-ratio results in a 92.6% hit rate of the GBS group and 16.7% false positives of the MBS group. The resulting normal deviates are 1.446 below the mean and 0.967 above the mean, respectively, for the GBS group and the MBS group, resulting in a sensitivity index $d'$ (or discriminating performance) of 2.414.

To what extent this sensitivity index is associated with the maximal discriminative power, can be demonstrated by calculating the expected value of the WRRT-ratio criterion. The expected value reflects the performance of a test by positively incorporating the hit rates and the correct rejections and negatively incorporating the false positives and the false negatives. By varying the false positives and false negatives, the optimal expected value can be determined and thus the highest discriminative power. At the WRRT-ratio criterion found the sensitivity index $d'$ of 2.4 had an expected value of 0.82, which was 1.2% less than the optimal expected value of 0.83.

V. DISCUSSION

Viewing stereoscopic displays may cause visual discomfort (asthenopia) for a relatively limited number of people. We performed an experiment to identify easily applicable indicators of visual discomfort in relation to stereoscopic 3-D displays. Participants were asked to perform the WRRT at various levels of screen disparity. Based on Evans’ [13] criterion, participants were differentiated into two subgroups: those with a GBS and those with a MBS. Our results reveal that participants with a MBS experience more asthenopic complaints (already at a screen disparity of 0.75°) and have a poorer reading performance at higher screen disparities than participants with GBS. This indicates that the ratio of number of words read between 2-D and 3-D crossed screen disparity (WRRT-ratio) is able to categorize people based on their binocular status.

These results are in line with our previous experiment in which the WRRT-ratio also significantly differed between subgroups with a GBS and a MBS [10]. The cut-off ratio to distinguish between subgroups in the current experiment, however, is lower (1.25 compared to an average WRRT-ratio of 1.5 in the previous experiment). This may be associated with the difference in viewing distance. A near viewing distance gives participants a greater opportunity to adjust accommodation, which may account for the lower ratio for all participants. Even so, the ratio remains a useful predictor for subjects with binocular vision anomalies. In research concerning reading difficulties, causal relationships are not fully understood. Poor reading performance can be easily correlated with visual problems, yet it is more difficult to claim causality [58]; people without visual problems may have reading difficulties as well, and people with visual problems may have no reading difficulties at all [59]. It is not the intention of the experiment to establish causality between reading performance and people’s binocular status. Reading speed, however, depends strongly on image quality [60]. Since the virtual reading distance changes in accordance with the virtual stimulus size, the quality remained the same for all conditions. Hence, the WRRT-ratio only reflects the impact of screen disparity. For good stereoscopic depth perception, precise coordinated alignment of the two eyes is required [61], [62]. Hence, people with deficits in their binocular system (inadequate fusion, a decompensated heterophoria or a clinically significant fixation disparity) have more problems with saccades or with return sweeps to the beginning of the next line [13].

With respect to the second hypothesis, the vergence facility (non-significantly) is poorer in the MBS subgroup than in the GBS subgroup. The average performance in both groups, however, does not reach the norm of 15 cycles per minute [40], which is in line with the results of our previous research [10].

### TABLE III

<table>
<thead>
<tr>
<th>WRRT-Ratio Pass</th>
<th>WRRT-Ratio Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>GBS 25 (hit rate)</td>
<td>2 (false negative)</td>
</tr>
<tr>
<td>MBS 1 (false positive)</td>
<td>5 (correct rejection)</td>
</tr>
</tbody>
</table>

Fig. 6. (a) Number of words read per minute as a function of disparity and binocular status. (b) Ratio of number of words read in 2-D and 3-D as a function of disparity for both subgroups.
Since previous research also reveals that the vergence facility for large viewing distances lacks good specificity (the ability to correctly identify people without a specific condition) [8], and has poor repeatability [40], the tool appears inadequate to differentiate subgroups by itself.

With respect to the third hypothesis, accommodation facility appears inappropriate to enable identification of participants with a MBS. All participants had similar accommodative functions and none of the participants are more than one standard deviation below the mean for normal subjects (as reported in [54]).

What may appear counter-intuitive is that on one hand we claim that there is no single method to identify people with binocular dysfunctions, while on the other hand we claim a single performance tool is useful to categorize people according to their BS. Though Evans’ algorithm makes a reliable and valid distinction in subgroups based on binocular status, it is a multifactorial test that is complex, time-consuming, and requires equipment that is not available in most research facilities or in any home environments. We suggest that the WRRT-ratio is a more accessible indicator of people whose binocular status might make 3-D viewing problematic. The criterion of an abnormal WRRT-ratio had a 93% specificity (ability to correctly identify people without a specific condition) and an 83% sensitivity (ability to correctly identify people with a specific condition), and a high discriminating power, a sensitivity index of 2.4. There is little reason to change this criterion in order to obtain a higher sensitivity index, since the expected value can be maximally increased by 1.2%. Since it must be acknowledged that our research has thus far included fairly modest sample sizes (only six subjects in the MBS group) further research with more participants is necessary to determine the stability of this sensitivity. In addition, since only young and healthy people were included, people with large refractive errors, strabismus, and amblyopia, and children, older people, and people with visual impairment, should also be included.

In summary, the WRRT-ratio seems appropriate for detecting people who are susceptible to visual complaints associated with stereoscopic displays. Indeed, we believe that this test may have potential for future international standardization of guidelines on image safety [63]. For example, participants in 3-D perceptual research most often are not visually screened. This test is indicative of BS and can be added to stereo and visual acuity tests. Future research should reveal if participants with a MBS who are identified via the WRRT-ratio indeed have lower comfortable screen disparity limits than people with normal binocular status. If so, the test can be used in consumer applications to set individual norms for comfortable screen disparities based on viewers’ binocular status.

VI. CONCLUSION

The home consumer market is progressing toward 3-D movies and games in the comfort of the living room. Research concerning visual complaints related to stereoscopic displays is socially broadly based, since part of the population has some binocular deficit which could lead to visual complaints when viewing stereoscopic content. It appears difficult to identify these people in other ways before they perform stereoscopic perceptual experiments, watch 3-D movies, or play 3-D games, since it requires optometric screening to evaluate their binocular status objectively.

Our research provides information on which optometric indicators (subjective, objective, and performance based) may help predict which persons experience visual discomfort when viewing stereoscopic displays. As a relatively simple indicator, the ratio of performance of the WRRT between 2-D and 3-D in crossed disparity may help to detect people who are susceptible to visual fatigue when viewing stereoscopic displays. Even though the specific ratio depends on the virtual viewing distance, it is consistent with susceptibility; participants who are susceptible have poorer reading performance in 3-D than in 2-D compared to people with normal binocular vision. Such a relatively simple tool has potential to serve in consumer applications to set individual norms for comfortable screen disparities based on viewers’ binocular status. Further research with larger numbers of participants is recommended.

ACKNOWLEDGMENT

The authors would like to thank the optometrists A. Faber and L. A. Aman for their support in the acquisition of data during this study and the Department of Optometry, Hogeschool Utrecht, University of Applied Science, Utrecht, The Netherlands, for the use of their clinical facilities.

REFERENCES

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Susceptibility to Visual Discomfort of 3-D Displays by Visual Performance Measures

Marc Lambbooij, Marten Fortuin, Wijnand A. IJsselsteijn, Bruce JW Evans, and Ingrid Heynderickx

Abstract—People with some signs of binocular dysfunctioning can be susceptible to visual complaints associated with viewing stereoscopic content at large viewing distances. Two performance measurements enabled to distinguish people by their binocular status (BS) in previous research: the ratio of performance of the Wilkins rate of reading test (WRRT) between 2-D and 3-D, and the vergence facility. In an experiment, first, an extensive optometric screening was carried out to differentiate visually asymptomatic young adults with good BS (GBS) (N = 27) from those with a moderate BS (MBS) (N = 6). Second, participants had to perform the WRRT at short viewing distance followed by a questionnaire under different screen disparity settings. The results reveal that the ratio of the WRRT between 0 and −1.5 screen disparity is an appropriate indicator of participants with MBS in comparison with participants with GBS. In addition, the results show that 0.75° of screen disparity is already problematic for people with MBS. We conclude that the WRRT-ratio has potential as a BS test in consumer applications to provide individual settings for comfortable screen disparities based on viewers’ BS.

Index Terms—3-D displays, optometric measurement, reading speed, stereo vision, visual discomfort, visual performance.

I. INTRODUCTION

STEREOSCOPIC movies boost the viewing experience by rendering content in front of or behind the display plane; yet numerous studies have reported an association with visual complaints [1]–[10]. The effects of stereoscopic content on visual discomfort vary among people since visual functions differ [2], [10]–[12]. When constructing guidelines for the creation and viewing of 3-D content it is important to take account of the range of visual functions that are likely to be encountered in viewers.

The visual system of the majority of people may be characterized as normal, yet there still are differences in performance between them. There is a paucity of epidemiological data on the prevalence of binocular vision anomalies, but some degree of binocular anomaly affects approximately 10–20% of patients consulting community optometrists [13], with the wide range of figures in this review reflecting inconsistencies in the underlying literature [14]–[19]. Severe binocular anomalies such as strabismus (squint) and amblyopia (lazy eye) typically prevent stereopsis. So-called non-strabismic binocular anomalies permit stereopsis, but predispose the patient to asthenopia (eyestrain and headaches). These visual complaints may not be present in normal viewing situations, but may occur or become more severe in unnatural viewing situations, such as viewing stereoscopic content.

In the case of stereoscopic near work, visual complaints can solely result from accommodative dysfunctions. These accommodative dysfunctions affect up to 16% of patients consulting community optometrists [17], [18], though this prevalence is much higher (60%) among patients receiving treatment for binocular anomalies [18], [19]. The symptoms of both binocular and accommodative anomalies are diverse and nonspecific, which complicates the relationship between people’s binocular functioning and the occurrence of visual complaints for stereoscopic near work. Clinically, the diagnosis of these conditions is based on several subjective and objective methods, in combination with the practitioner’s knowledge and experience. In other words, the identification of people with poorer accommodative and binocular visual functioning has hitherto involved extensive optometric testing.

If participants who are prone to visual complaints associated with stereoscopic viewing as a consequence of their binocular functioning can be detected by a simple test of reading performance then this has two important implications. First, such a test could be used in perceptual research, perhaps complementing the information provided by stereo acuity and visual acuity tests. Second, this test could be a useful tool in consumer applications to individually set comfortable screen disparities based on viewers’ binocular status (BS).
II. BACKGROUND

A. Binocular Functioning

To obtain clear, binocular single vision, the visual system maintains accommodation and convergence that are appropriate for the viewing distance. Vergence can be defined as the movement of the eyes in opposite directions to maintain fixation on an object that is moving in depth. The vergence system is primarily retinal disparity-driven and resolves mismatches in the fusion system [18], [20]. In most cases, the vergence system compensates for binocular anomalies such as heterophoria (the tendency of the eyes to misalign when they are dissociated) or fixation disparity (the minimum angular measure of misalignment of the visual axes of the eyes). People with inadequate fusion or an excessive heterophoria may require more effort to maintain fusion. This may lead to visual complaints when viewing stereoscopic content [13], [21]-[23]. In this case, the heterophoria is described as decompensated and may be associated with clinical signs such as fixation disparity [15], [24], for a review see [13].

Accommodation concerns the alteration of the crystalline lens to obtain and maintain the object of interest with the highest attainable resolution focused on the fovea. The accommodation system is primarily driven by retinal blur and can compensate for small errors in specific accommodative dysfunctions [7], [9], [18], [20]. In unnatural or stressful viewing situations, such as stereoscopic near work, people with smaller tolerance in their accommodative functioning can expend so much effort that visual complaints may arise [17], [21], [22], [25]-[28].

The literature described above generally supports the need for clinically testing people before they participate in stereoscopic perception experiments, and ideally before they view stereoscopic full-feature movies or participate in other simulated 3-D viewing environments. This is because simulated 3-D content creates artificial viewing conditions, most notably by creating a different stimulus to vergence and accommodation [1], [9].

For diagnosing binocular dysfunctions no single test is 100% effective or objective [29]. In view of this, Evans [13], [30] constructed an algorithm (described in Section III-B) for diagnosing decompensated heterophoria that computes a score representative of a person’s BS. This algorithm has been used in previous research to provide an index of the BS of heterophoric subjects, that is the degree to which their heterophoria is compensated [31]. In a recent study, this algorithm was applied to discriminate people with normal binocular functioning from those with moderate BS (MBS), and consequently, with a higher susceptibility to visual complaints associated with viewing stereoscopic displays at a large viewing distance [10]. Seven of the 39 participants (18%) were identified as people with a MBS. After short-term stressful stereoscopic reading tasks at a viewing distance of three meters these seven participants revealed objective signs of visual fatigue and indicated more visual discomfort in contrast to those participants with a good BS (GBS).

In case of stereoscopic near work, participants should be screened for both binocular and accommodative functioning. Dysfunctions in either systems can cause similar, nonspecific, visual complaints including blurred, double, or distorted vision, difficulty in changing focus, headache, acheing eyes, sore eyes, and irritated eyes [17], [18], [28], [29]. Hence, it is not that straightforward to determine whether a symptom associated with stereoscopic near work is attributable to a binocular vision anomaly, an accommodative dysfunction, to both, or maybe even another condition, e.g., dry eyes.

B. Reading Performance

Reading difficulties are a common symptom in people with visual dysfunctions [32]. It is widely reported that visual deficits (e.g., visual acuity, fixation disparity, fusion, accommodation, vergence, and visual stress) can impair reading ability and induce visual complaints when reading [32]-[36].

For people with accommodative dysfunctions test will be out of focus, which may impair reading performance since blur impedes resolving detail. For people with binocular dysfunctions, text may appear doubled, blurred, or distorted due to vergence errors while making saccades or making return sweeps at the end of the line [13], [34].

The extent of these reading impairments can be properly assessed with the Wilkins rate of reading test (WRRT) [36]-[39]. The WRRT will be discussed in more detail in Section III-D. It was originally developed to assess symptoms that are alleviated by using colored filters of a specific tint while reading [37]. Jeanes et al. [34] reported that children who benefit from using colored filters, showed an improvement in performance of 8% with the WRRT. O’Leary and Evans [36] found that correcting decompensated heterophoria improved performance at the WRRT. Lambooij et al. [10] revealed that people with a MBS classified by Evans’ algorithm [30] showed a significantly higher ratio in performance of the WRRT between 2-D and 3-D than people with GBS. In the rest of this paper, the WRRT-ratio is used to describe the ratio calculated from (number of words read in 2-D)/(number of words read in 3-D). Participants with a MBS had on average a WRRT-ratio of 1.8, whereas participants with a GBS had on average a WRRT-ratio of 1.5. In other words, the adverse effect of screen disparity on reading performance was larger for people with a MBS than for people with a GBS.

C. Facility Measurement

An indication of a normal visual system is proper adaptation and sufficient facility to respond to alterations in the viewing environment [23]. Vergence facility is the ability of the functional vergence system to respond efficiently and accurately to changing demands over time [40]. Vergence facility testing improves the diagnosis of binocular dysfunctions [40] and is an indicator of readiness for binocular visual tasks [17], [41]. The research of Lambooij et al. [10] revealed that participants with a MBS, who experienced more visual complaints associated with stereoscopic reading tasks, had a lower vergence facility than participants with a GBS. Analogously, accommodation facility is the ability of the accommodative visual system to respond efficiently and accurately to changing demands over time [42]. It is used as an indicator of readiness for near
vision tasks [17], [42]. Testing accommodation facility under binocular test conditions provides: 1) a direct evaluation of the dynamics of accommodative response similar to under monocular test conditions, and 2) information about the coupling between accommodation and vergence [13], [40], [42]. As such it is also referred to as interactive facility and seems appropriate for stereoscopic near work.

D. Hypotheses

The current research aims: 1) to provide further data on the proportion of people who are susceptible to such visual complaints, and 2) to construct relatively simple performance measurements that can be used to identify a subgroup of participants who might be more susceptible to visual complaints associated with stereoscopic displays at shorter viewing distance.

As stated, Lambooij et al. [10] revealed that susceptibility to visual complaints associated with modern stereoscopic displays can be detected by relatively simple visual performance measures (i.e., reading performance and vergence facility measurement). Since a relatively large viewing distance (3 m) was used in that research, the current research is focused on stereoscopic near work. This may complicate the analysis of the relationship between people’s BS and the occurrence of visual discomfort as a consequence of screen disparity, accommodative dysfunctions might have a perceptual impact as well. In addition, Lambooij et al. [10] used only two screen disparities: zero and 1.5\(^\circ\) crossed disparity. To obtain a relationship between visual performance and visual discomfort as a consequence of screen disparity, the current research incorporates more screen disparities.

Participants with normal visual functioning are categorized via an extensive optometric screening into two subgroups: one with a GBS and one with a MBS. It is noteworthy that the original aim was to construct a subgroup of participants with accommodative dysfunctions as well, yet all participants appeared to have proper accommodative status. Three relatively simple indicators are evaluated in terms of their ability to confirm this distinction in subgroups: the WRRT-ratio, the vergence facility, and the accommodative facility.

The former two showed potential to categorize people based on their BS, which determined their susceptibility to visual discomfort associated with viewing stereoscopic displays for a large viewing distance [10]. The latter is incorporated since accommodative dysfunctions may also impact the ability to comfortably view (stereoscopic) content for close viewing distances. The facility measurements are two tests that are not included in Evans’ algorithm and are thought to be most relevant as potential predictors of problems when viewing 3-D displays.

The first hypothesis states that the WRRT-ratio is effective to distinguish people that are more susceptible to visual complaints associated with stereoscopic displays for close viewing distances. The second hypothesis states that vergence facility measured at large viewing distances distinguishes people by their susceptibility to visual complaints associated with stereoscopic near work. The third hypothesis states that for near vision, accommodation facility is a useful indicator to differentiate people’s susceptibility to visual complaints associated with stereoscopic displays.

III. EXPERIMENTAL SET-UP

A. Design

The experimental design consisted of two parts: 1) an optometric screening, and 2) the performance of the WRRT for close viewing distance. The optometric screening included accommodation and vergence facility measurements and facilitated categorization of participants based on their BS: GBS (N = 27) and MBS (N = 6). Neither the participants nor the experimenter knew to which subgroup a participant belonged during the experiment.

In the second part, the WRRT was performed via a Wheatstone viewer under five screen disparity settings (disparity): 1.5, 0.75, 0, −0.75, and −1.5 degrees, where a “−” sign indicates crossed screen disparity. Different WRRTs were assigned randomly to the five screen disparity settings of which the order was randomized across participants. After each WRRT, the subjective visual discomfort was evaluated with a questionnaire containing 15 subjective items (Item). The entire experiment (screening part and experimental parts) was scheduled on one day.

B. Screening of Participants

An extensive optometric screening was carried out on 33 naive visually asymptomatic participants of age range 18–36 years. This screening was performed for two reasons: 1) to exclude participants with eye diseases or severe binocular abnormalities, such as partial (stereo) blindness, large refractive errors (> 0.50 diopter (D)), strabismus, and amblyopia, and 2) to differentiate participants in subgroups based on their visual functioning. Subgroups were assembled based on the optometric screening carried out at near vision distances (40–70 cm). All optometric indicators with their exclusion criteria are described in detail in our previous papers [8], [10]. In this paper, only those indicators used to construct the subgroups are discussed.

The categorization of participants based on their BS was established with an optometric algorithm described by Evans [13], [30]. The algorithm can be carried out in two stages: an abbreviated version to rapidly classify normal subjects as such (based on six test results; items 1–6 in Table I) and a more detailed version (which is recommended especially for patients who do not achieve good results on the first six tests) in which four further tests are completed (items 7–10 in Table I). The full version (all ten tests) was used in the present research. This full algorithm calculates the sum of ten scores of which is the result of a single optometric indicator of decompensated heteroanopia (including binocular instability), yet none of which individually is diagnostic of BS by itself [8].

The total algorithm score ranges from 0 to 16; a score of 0–5 is normal and 6 or more abnormal [13], [30]. In this paper, scores of 0–5 inclusive were classified as GBS (27 participants) and 6 or higher as MBS (six participants). The term MBS is used rather than a stronger term (e.g., pathological binocular status).
in recognition of the fact that people with strabismus were excluded from the research.

The algorithm and scoring system are based on a review of the literature [13], [30] and clinical experience using prototypes of the algorithm in the Institute of Optometry clinics over a number of years. The algorithm and scoring system was first described in 1997 [30] and also (unchanged) in subsequent publications [13], [43]–[45]. The published algorithm and scoring system has also been used in previous research as a measure of the degree to which heterophoria is compensated [31] and the decision was therefore made to use the same scoring system and definitions of normal/abnormal as those previously used.

To detect the symptoms that are suggestive of binocular dysfunctions (the first indicator in the algorithm), the convergence insufficiency symptom survey (CISS) was used that incorporates general asthenopic items [10], [21], [46]. Since the CISS questionare also incorporates items that relate to reading tasks specifically, it was also used in the actual experiment.

For the objective indicators, a short explanation is given here, though the authors would like to refer to Evans [13] for a more extended description. The cover test assesses ocular alignment (e.g., heterophoria) by covering each eye in turn. Fixation disparity is an angular measure of small misalignments of the visual axes of the eyes, which, if measured with a central fusion lock, provides a more accurate indication of the objective eye position than without a central fusion lock [47]. Aligning prism measures the minimum power of prism that corrects the fixation disparity [15], [24], [48]–[50]. Foveal suppression refers to a very small suppression area that occurs in the foveal region. Convergent and divergent fusional ranges indicate the amount of convergence and divergence, respectively, that can be induced before fusion is compromised. They are commonly characterized with prism loads at which binocular single vision becomes blurred (blur point), is lost (break point), and recovers again (recovery point). The fusion amplitude describes the amplitude between corresponding convergent and divergent fusion blur points. Percival’s and Sheard’s criteria refer to a fusion range that still allows comfortable fusion [51]. Percival’s criterion is defined as the middle third of the “zone of clear, single binocular vision.” This zone can be determined by measuring the blur points of fusion amplitude, i.e., the points at which clear vision is lost. In contrast to Percival’s criterion, Sheard’s criterion takes account of the heterophoria; it states that the opposing blur point should be at least twice the degree of the heterophoria [52], [53].

For the detection of accommodative dysfunctions, suggestions have been made about which accommodation indicators should be included in an optometric screening [17]. An objective protocol of diagnosis to clearly distinguish the subgroup with poor accommodative status, however, is not available to our knowledge. Table II lists the accommodative indicators with poor accommodative status, however, is not available to our knowledge. Table II lists the accommodative indicators with poor accommodative status, however, is not available to our knowledge.
screen shot of a stimulus. Only the text was presented with stereoscopic depth, whereas the frame with the circles was presented at zero disparity. The frame was added around the screen shot in order to maintain the appropriate viewing distance, and to obtain a clear and single image. The initial setting of the stimulus was always with zero screen disparity, yet participants were able to increase the screen disparity stepwise by pressing keypad number 8 (up arrow). Except in the 2-D condition, depending on the condition of the stimulus the WRRT changed in stereoscopic depth: either in crossed or uncrossed disparity. If participants had trouble fusing the stimuli, keypad number 2 (down arrow) could be used to decrease the screen disparity. This stepwise altering of the screen disparity to set any of the five screen disparities (−1.5, −0.75, 0, 0.75, and 1.5 degrees) was included since previous research revealed that not all participants were able to fuse 1.5° of screen disparity in a single step [10]. Hence, participants could increase the screen disparity to the value that belonged to that condition. Once the appropriate screen disparity was set, the participants were asked to read the words “out loud”...

### TABLE I

**Algorithm Proposed by Evans [30] Applied to Differentiate Participants with Respect to Their Binocular Status Based on Objective and Subjective Optometric Indicators [13, 30]**

<table>
<thead>
<tr>
<th>No.</th>
<th>No. Indicators</th>
<th>Sign or Symptom</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Symptomatic heterophoria</td>
<td>One or more of the questionnaire symptoms (if so, +3 or +2 or +1 if borderline)</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Cover test</td>
<td>Heterophoria detected</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Cover test</td>
<td>Absence of rapid and smooth recovery (if so, +2 or +1 if borderline)</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Fixation disparity with fusion lock</td>
<td>Aligning prism (Mallet): &gt;1 PD patients under 40 or &gt;2 PD patients over 40</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Fixation disparity with fusion lock</td>
<td>Aligning prism (Mallet): unstable</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Foveal suppression</td>
<td>Foveal suppression (Mallet): &gt;3 arcmin</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>Sheard's criterion</td>
<td>Failed</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>Percival's criterion</td>
<td>Failed</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>Dissociated heterophoria</td>
<td>Unstable (if range &gt; 4 PD)</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>Fusion amplitude</td>
<td>≤20 PD</td>
<td>1</td>
</tr>
</tbody>
</table>

PD: prism diopter.

### TABLE II

**Mean Values and Standard Deviations of Accommodation Indicators for Participants with GBS and MBS, as well as the Corresponding Normal Values**

<table>
<thead>
<tr>
<th>Indicators</th>
<th>GBS Mean ± STD</th>
<th>MBS Mean ± STD</th>
<th>Norm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accommodation amplitude (binocular push up test)</td>
<td>9.20 ± 1.91</td>
<td>9.44 ± 0.86</td>
<td>15 ± 0.35 (age)</td>
</tr>
<tr>
<td>Negative relative accommodation</td>
<td>2.44 ± 0.50</td>
<td>2.38 ± 0.85</td>
<td>2.40 ± 0.50</td>
</tr>
<tr>
<td>Positive relative accommodation</td>
<td>2.50 ± 1.11</td>
<td>2.13 ± 0.95</td>
<td>2.37 ± 1.12</td>
</tr>
<tr>
<td>Accommodation response (MEM-retinoscopyb)</td>
<td>0.48 ± 0.37</td>
<td>0.67 ± 0.26</td>
<td>0.35 ± 0.35</td>
</tr>
<tr>
<td>Accommodation facility (±2-D lenses)</td>
<td>14.07 ± 4.44</td>
<td>13.00 ± 5.14</td>
<td>8 ± 5</td>
</tr>
</tbody>
</table>

aUnits are in diopters except accommodation facility that is expressed in number of cycles per minute.
bMEM abbreviates monocular estimation method.

*Reference [54].

E. Questionnaire Items

The CISS questionnaire included the following items: discomfort, loss of concentration, double vision, sleepiness, sharpness, exhaustion, appearance of moving words, slower reading, losing position in text, trouble remembering words, re-reading words, headache, pain in the eyes, strain in the eyes, and irritated eyes [46]. Participants were asked to assess the items on a scale labeled with the adjective terms: never/infrequently/sometimes/fairly often/always.

F. Procedure

Participants were provided with an informed consent form containing information about the screening and the experiment, such as the general procedure and the possible occurrence of visual discomfort. After signing the informed consent, they proceeded with the optometric screening, which required about 25 min to complete. They received a brief instruction about the specific course of the experiment that incorporated a version of the WRRT to familiarize participants with the specific reading task. All questions concerning the procedure of the experiment were answered, after which the experiment started.

Participants had to properly rest their head against the screenscope in order to maintain the appropriate viewing distance, and to obtain a clear and single image. The initial setting of the stimulus was always with zero screen disparity, yet participants were able to increase the screen disparity stepwise by pressing keypad number 8 (up arrow). Except in the 2-D condition, depending on the condition of the stimulus the WRRT changed in stereoscopic depth: either in crossed or uncrossed disparity. If participants had trouble fusing the stimuli, keypad number 2 (down arrow) could be used to decrease the screen disparity. This stepwise altering of the screen disparity to set any of the five screen disparities (−1.5, −0.75, 0, 0.75, and 1.5 degrees) was included since previous research revealed that not all participants were able to fuse 1.5° of screen disparity in a single step [10]. Hence, participants could increase the screen disparity to the value that belonged to that condition. Once the appropriate screen disparity was set, the participants were asked to read the words “out loud”...
Fig. 1. Mallett near vision unit on which the polarized nomius lines were aligned by using rotary prisms while the subject viewed the small OXO test figure (the instrument is normally internally illuminated). Test instructions followed guidelines of [15].

Fig. 2. Principle of the screenscope, the stereoscopic system used in the experiment to direct the left-eye and right-eye image of a side-by-side displayed stereo pair to the appropriate eyes. The viewing distance (A+B+C) was 0.40 m.

as rapidly as possible for 60 s. It was emphasized that the text needed to be in focus (sharp) and single. Each reading task was followed by the CISS questionnaire and a rest period of approximately 2 min to relax the eyes. The participants were instructed that each time the CISS questionnaire was carried out their responses should relate to symptoms during the experimental condition that had just taken place. This entire procedure was performed five times (i.e., for five different disparity conditions) with the conditions randomized across participants. The experimental session required about 20 min.

IV. Results

As explained in Section III-B, two subgroups were identified based on their visual functioning: participants with a good binocular status (N = 27) and participants with a moderate binocular status (N = 6), referred to as GBS and MBS, respectively.

A. Subjective Results

Most of the CISS items yielded an averaged visual discomfort score around two, referring to moderate levels of visual discomfort. Not all items were affected similarly by changes in disparity or experienced equally by the two subgroups of participants. A principal component analysis (PCA) was performed to find intrinsic correlations between the 15 items and to reveal if certain items shared similar underlying attributes of visual discomfort [56]. The PCA was combined with a non-orthogonal rotation method (Oblimin) to minimize the number of items with high factor loadings on more than one factor. The resulting PCA revealed two underlying factors that explained 39% and 19% of the variance of the data. Factor 1 received meaningful factor loadings (> .50 [56]) of the items moving words, slower reading, sharpness, loss of position in text, rereading words, and double vision and relates to misperception of text. Factor 2 consisted of exhaustion, headache, pain, strain, and discomfort and relates to asthenopia. Reliability testing revealed Cronbach’s alphas of 0.84 and 0.75 for factors 1 and 2, respectively (a Cronbach’s alpha of > 0.70 is considered acceptable [56]). The items concentration problems, sleepiness, irritated eyes, and remembering words received a low factor loading on both factors 1 and 2. Based on the reliability analysis it was decided to exclude these items from further analysis. For each participant, a factor score was calculated for each factor in each condition, i.e., the score given by the participant on each questionnaire item was weighted with the factor loading of that item, and then summed over all items of the factor [50]. An analysis of variance (ANOVA) with BS and disparity as independent variables revealed that factor 1 was significantly affected by disparity (F(1, 155) = 2.553, p < 0.05). Factor 2 was significantly affected by BS (F(1, 155) = 14.810, p < 0.001), disparity (F(4, 155) = 4.747, p < 0.05) and the interaction between BS and disparity (F(4, 155) = 2.780, p < 0.05). The results are depicted in Fig. 4 for factors 1 (upper panel) and 2 (lower panel). It is noteworthy that there is a significant increase in factor 2 for the MBS group when a disparity of 0.75 degrees was reached.

Fig. 3. Screen shot of the stimulus; a passage of the WRRT [37].
Fig. 4. Mean visual comfort factor scores of the two sets of questionnaire items: (a) factor 1 and (b) factor 2. The x-axes represent the different screen disparities, the y-axes the average factor scores, and the different lines in the lower panel the two subgroups.

B. Accommodation and Vergence Facility

Fig. 5 depicts the average measurement results of the accommodation facility (upper panel) and vergence facility (lower panel) per BS subgroup including the 95% confidence intervals and norm values.

A multivariate ANOVA revealed no statistically or clinically significant differences between the two different BS subgroups in terms of their accommodation facility ($p = 0.337$) and vergence facility ($p = 0.202$).

C. WRRT Performance

The upper panel of Fig. 6 depicts the number of words read as a function of disparity for both subgroups, whereas the lower panel of Fig. 6 depicts the ratio of words read in 2-D compared to 3-D as a function of disparity for both subgroups.

Concerning the data illustrated in the upper panel of Fig. 6, an ANOVA revealed that the performance at the WRRT (i.e., number of words read) did not significantly differ between levels of disparity ($F(4, 155) = 2.070, p = 0.087$) or between the BS subgroups ($F(1, 155) = 1.211, p = 0.273$). There is a clear effect visible, however, of disparity on the performance of the WRRT for the MBS subgroup, but this was not significant. It is plausible that this is due to the small number of participants in this group ($N = 6$). The analysis of the ratio of the number of words read between 2-D and 3-D, i.e., WRRT-ratio in the lower panel of Fig. 6, revealed that BS ($F(3, 124) = 23.805, p < 0.001$) and disparity ($F(3, 124) = 3.751, p < 0.05$) had a significant effect on this ratio.

A reverse analysis should reveal if this WRRT-ratio can be used to predict the BS, i.e., distinguish the MBS subgroup from the GBS group.

For the reverse analysis, only the WRRT-ratio of the 1.5 crossed screen disparity was used, i.e., $-1.5°$. It revealed a large difference in WRRT-ratio between both subgroups and small variances per subgroup, whereas the variance of the WRRT-ratio in the uncrossed screen disparity was much higher for both subgroups. Hence, the crossed screen disparity condition appeared most appropriate. Since the implementation of a tool should be as simple as possible, a cut-off value of 1.25 in the WRRT-ratio was chosen which is the mean plus one STD of all participants, i.e., $1.10 + 0.15$. Table III depicts the distinction accomplished by the WRRT-ratio when applying this limit.

The discriminating performance of the WRRT-ratio criterion can be reflected by the sensitivity index $d'$ [57]. The sensitivity index is defined as the standardized distance between the
Fig. 6. (a) Number of words read per minute as a function of disparity and binocular status. (b) Ratio of number of words read in 2-D and 3-D as a function of disparity for both subgroups.

TABLE III

<table>
<thead>
<tr>
<th></th>
<th>WRRT-Ratio Pass</th>
<th>WRRT-Ratio Fail</th>
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</thead>
<tbody>
<tr>
<td>GBS</td>
<td>25 (hit rate)</td>
<td>2 (false negative)</td>
</tr>
<tr>
<td>MBS</td>
<td>1 (false positive)</td>
<td>5 (correct rejection)</td>
</tr>
</tbody>
</table>

means of both subgroups and is calculated by the difference between the normal deviates of the hit rates and false positives.

Calculation of \( d' \) entails the assumption that both subgroups have stochastic responses that are normally distributed and that all quadrants of the contingency matrix have equal impacts.

The criterion of the WRRT-ratio results in a 92.6% hit rate of the GBS group and 16.7% false positives of the MBS group. The resulting normal deviates are 1.446 below the mean and 0.967 above the mean, respectively, for the GBS group and the MBS group, resulting in a sensitivity index \( d' \) (or discriminating performance) of 2.414.

To what extent this sensitivity index is associated with the maximal discriminative power, can be demonstrated by calculating the expected value of the WRRT-ratio criterion. The expected value reflects the performance of a test by positively incorporating the hit rates and the correct rejections and negatively incorporating the false positives and the false negatives. By varying the false positives and false negatives, the optimal expected value can be determined and thus the highest discriminative power. At the WRRT-ratio criterion found the sensitivity index \( d' \) of 2.4 had an expected value of 0.82, which was 1.2% less than the optimal expected value of 0.83.

V. DISCUSSION

Viewing stereoscopic displays may cause visual discomfort (asthenopia) for a relatively limited number of people. We performed an experiment to identify easily applicable indicators of visual discomfort in relation to stereoscopic 3-D displays. Participants were asked to perform the WRRT at various levels of screen disparity. Based on Evans’ [13] criterion, participants were differentiated into two subgroups: those with a GBS and those with a MBS. Our results reveal that participants with a MBS experience more asthenopic complaints (already at a screen disparity of 0.75°) and have a poorer reading performance at higher screen disparities than participants with GBS. This indicates that the ratio of number of words read between 2-D and 3-D crossed screen disparity (WRRT-ratio) is able to categorize people based on their binocular status.

These results are in line with our previous experiment in which the WRRT-ratio also significantly differed between subgroups with a GBS and a MBS [10]. The cut-off ratio to distinguish between subgroups in the current experiment, however, is lower (1.25 compared to an average WRRT-ratio of 1.5 in the previous experiment). This may be associated with the difference in viewing distance. A near viewing distance gives participants a greater opportunity to adjust accommodation, which may account for the lower ratio for all participants. Even so, the ratio remains a useful predictor for subjects with binocular vision anomalies. In research concerning reading difficulties, causal relationships are not fully understood. Poor reading performance can be easily correlated with visual problems, yet it is more difficult to claim causality [58]; people without visual problems may have reading difficulties as well, and people with visual problems may have no reading difficulties at all [59]. It is not the intention of the experiment to establish causality between reading performance and people’s binocular status. Reading speed, however, depends strongly on image quality [60]. Since the virtual reading distance changes in accordance with the virtual stimulus size, the quality remained the same for all conditions. Hence, the WRRT-ratio only reflects the impact of screen disparity. For good stereoscopic depth perception, precise coordinated alignment of the two eyes is required [61], [62]. Hence, people with deficits in their binocular system (inadequate fusion, a decompensated heterophoria or a clinically significant fixation disparity) have more problems with saccades or with return sweeps to the beginning of the next line [13].

With respect to the second hypothesis, the vergence facility (non-significantly) is poorer in the MBS subgroup than in the GBS subgroup. The average performance in both groups, however, does not reach the norm of 15 cycles per minute [40], which is in line with the results of our previous research [10].
Since previous research also reveals that the vergence facility for large viewing distances lacks good specificity (the ability to correctly identify people without a specific condition) [8], and has poor repeatability [40], the tool appears inadequate to differentiate subgroups by itself.

With respect to the third hypothesis, accommodation facility appears inappropriate to enable identification of participants with a MBS. All participants had similar accommodative functions and none of the participants are more than one standard deviation below the mean for normal subjects (as reported in [54]).

What may appear counter-intuitive is that on one hand we claim that there is no single method to identify people with binocular dysfunctions, while on the other hand we claim a single performance tool is useful to categorize people according to their BS. Though Evans’ algorithm makes a reliable and valid distinction in subgroups based on binocular status, it is a multifactorial test that is complex, time-consuming, and requires equipment that is not available in most research facilities or in any home environments. We suggest that the WRRT-ratio is a more accessible indicator of people whose binocular status might make 3-D viewing problematic. The criterion of an abnormal WRRT-ratio had a 93% specificity (ability to correctly identify people without a specific condition) and an 83% sensitivity (ability to correctly identify people with a specific condition), and a high discriminating power, a sensitivity index of 2.4. There is little reason to change this criterion in order to obtain a higher sensitivity index, since the expected value can be maximally increased by 1.2%. Since it must be acknowledged that our research has thus far included fairly modest sample sizes (only six subjects in the MBS group) further research with more participants is necessary to determine the stability of this sensitivity. In addition, only young and healthy people were included, people with large refractive errors, strabismus, and amblyopia, and children, older people, and people with visual impairment, should also be included.

In summary, the WRRT-ratio seems appropriate for detecting people who are susceptible to visual complaints associated with stereoscopic displays. Indeed, we believe that this test may have potential for future international standardization of guidelines on image safety [63]. For example, participants in 3-D perceptual research most often are not visually screened. This test is indicative of BS and can be added to stereo and visual acuity tests. Future research should reveal if participants with a MBS who are identified via the WRRT-ratio indeed have lower comfortable screen disparity limits than people with normal binocular status. If so, the test can be used in consumer applications to set individual levels for comfortable screen disparities based on viewers’ binocular status.

VI. CONCLUSION

The home consumer market is progressing toward 3-D movies and games in the comfort of the living room. Research concerning visual complaints related to stereoscopic displays is socially broadly based, since part of the population has some binocular deficit which could lead to visual complaints when viewing stereoscopic content. It appears difficult to identify these people in other ways before they perform stereoscopic perceptual experiments, watch 3-D movies, or play 3-D games, since it requires optometric screening to evaluate their binocular status objectively. Our research provides information on which optometric indicators (subjective, objective, and performance based) may help predict which persons experience visual discomfort when viewing stereoscopic displays. As a relatively simple indicator, the ratio of performance of the WRRT between 2-D and 3-D in crossed disparity may help to identify people who are susceptible to visual fatigue when viewing stereoscopic displays. Even though the specific ratio depends on the virtual viewing distance, it is consistent with susceptibility; participants that are susceptible have poorer reading performance in 3-D than in 2-D compared to people with normal binocular vision. Such a relatively simple tool has potential to serve in consumer applications to set individual norms for comfortable screen disparities based on viewers’ binocular status. Further research with larger numbers of participants is recommended.

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