ORIGINAL INVESTIGATION

Measuring Virtual Reality Headset Resolution and Field of View: Implications for Vision Care Applications

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SIGNIFICANCE: To judge the feasibility of virtual reality (VR) headsets for vision testing and treatment of binocular vision disorders and low vision, angular resolution (logMAR) and field of view must be known and may not be reliably provided. This is the first study to measure the limitations of VR systems for eye care applications.

PURPOSE: This study aimed to measure, in a sample of VR headsets, eye-to-screen distance and other physical and optical characteristics needed to calculate minimum angular resolution in logMAR and field of view in determining feasibility for vision applications.

METHODS: Eye-to-screen distance was measured, and logMAR, field of view, and maximum convergence demand were calculated for two standalone VR devices, Oculus Rift DK2 and HTC Vive, and, for four smartphone VR headsets, Zeiss VR1, Samsung Gear VR, VR Box, and SunnyPeak, each paired with four high-resolution smartphones, Samsung Galaxy S7/S8, iPhone X, and LG VR30.

RESULTS: On average, the smallest letter that could be displayed in VR was 0.41 ± 0.09 (20/51), ranging from 0.59 (20/78) in the DK2 to 0.28 (20/39) in VR Box with S7. Mean field of view was 50.2 ± 4.8°, ranging from 39.6° in the VR Box with S7 to 55° in the HTC Vive. The mean field of view when used as a low vision aid was 23.0° and 12.7° for 2.2× and 4×, respectively. The mean maximum near convergence demand produced for a 60-mm interpupillary distance was 38.6 ± 10.1Δ.

CONCLUSIONS: The minimum angular resolution in logMAR of current VR technology is insufficient for visual acuity testing and may be insufficient for standalone treatment of amblyopia. Field of view during movie watching or gaming is about half that reported by manufacturers but adequate for some types of visual field testing. Use for vergence testing and training is a concern for headsets with long eye-to-screen distance or interpupillary distances <60 mm.

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Virtual reality headsets have recently emerged as a commercial product for 3D game play and movie watching for ages 10 years or greater. They offer promise for vision testing (e.g., visual field and acuity), for binocular vision therapy (e.g., amblyopia and convergence insufficiency treatment), and as a head-mounted low vision aid.[1–6] The virtual reality headset environment provides a controlled and compact environment where stimuli can be easily presented independently to each eye (dichoptic presentation) or create a 3D experience; however, there are major disadvantages to consider. These virtual reality systems either consist of a headset with a dedicated internal display (e.g., Oculus Rift [Oculus VR, Menlo Park, CA] and HTC Vive [HTC, New Taipei, Taiwan and Valve Corporation, Bellevue, WA]) or use a smartphone inserted into the headset (e.g., Samsung Gear VR with Galaxy phone [Samsung, Suwon, South Korea]). Regardless of the type of virtual reality headset, the display is positioned much closer to the eyes than traditional display viewing, requiring a high plus lens to correct for this close working distance. The close viewing distance results in relative distance magnification of the pixels, reducing the angular resolution of the display. This could be a major issue for visual acuity testing or amblyopia training applications that may require high spatial frequency stimuli. Manufacturers of virtual reality headsets do not provide angular resolution in their specification sheets, instead giving the pixel density of the display and some questionable report of field of view. Because the user field of view is dependent on the eye-to-screen distance, manufacturers may use an average distance, or they may not consider the user at all and simply use the size of the screen and the focal distance of the lens, which could overestimate the actual field of view for the user. It is also possible they will report the total field of view being the sum of the right and left eye fields, despite the fact that virtual reality displays present essentially identical images to each eye during 3D gaming and movie watching. Although there are slight differences in perspective to provide a stereo 3D experience, the total field of view experienced by the user is essentially the same under monocular and binocular viewing. Humphrey Visual Field Analyzer (Zeiss, Aalen, Germany) threshold field tests of 24–2 (48°) and 30–2 (60°) are considered the criterion standard, and so it is important to know which headsets would allow for a sufficient field of view for virtual reality–based field testing. For low vision, the virtual reality system can be used to provide magnification or image enhancement to the live image of the camera. Multiple virtual reality headset products are on the market such as IrisVision (IrisVision Global Inc., Pleasanton, CA) reporting 70° field of view, the Patriot ViewPoint (Patriot Vision Industries LLC, Ocala, FL) reporting a 101° field of view, and the NuEyes E2 (NuEyes llc, Newport Beach, CA) reporting a 101° field of view.[7–9] It is not clear what these marketed fields of view represent or how they were

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calculated. Reporting field of view without magnification taken into consideration can be misleading and makes comparison to standard telescopic aids difficult. For convergence binocular vision testing and training, the nasal field of view is important to allow for room to displace the fixation stimulus inward, and the capability of the virtual reality headset and display to allow for production of convergence demand up to normal amounts should be used to judge the system's feasibility for this application.[10–12] The normal positive fusional convergence (base-out) break point with Risley prisms for distance viewing (20 ft 6 m) has been reported as 19Δ (10.83°), and that for near (12.0°) Morgan's norms has been reported as 21Δ.[13] The near norm is in addition to the convergence demand for 40 cm, which varies with interpupillary distance (15Δ for a 60-mm interpupillary distance). Therefore, the total vergence demand needed to reach the normal near levels calculated from the distance neutral point for a 60-mm interpupillary distance is 36Δ (20.5°), or 18Δ per eye (10.3°). The high plus lens in the headset fixes the accommodative demand at or near zero (optical infinity), as though the eye was viewing the stimulus at 20 ft, assuming the patient is wearing his/her refractive correction for distance. This is identical to the distance Risley prism method in the phoropter and distance prism bar convergence range testing in free space. Accommodation is also fixed in many other testing and training devices (tranaglyphs, vectograms, computer orthoptics, and various other binocular vision devices and training tools) and is not unique to virtual reality headsets, which are a type of stereoscope. Accommodation demand of zero may cause some issues in comparing near virtual reality headset vergence ranges with near Risley prism vergences, except in absolute presbyopes or pseudophakes where they have no accommodation.

Given the potential for medical/ophthalmic use of virtual reality headsets, it is important to empirically evaluate the parameters that the user will experience. The purpose of this study was to carefully measure the parameters of the virtual reality headsets while considering how these may influence present and future vision testing and therapy applications. Our primary hypothesis was that current virtual reality headset and display combinations would not provide 0.0 logMAR (20/20 equivalent), which is widely considered to be the benchmark for normal visual acuity, making them insufficient for acuity testing[14] and likely suboptimal for amblyopia therapy. For any amblyopia treatment, it is reasonable that visual acuity improvement be linked to the acuity required for the training task. For example, to improve vision to 20/30, the training task should require visual discrimination of target sizes equivalent to or smaller than 20/30. For visual field testing, we expected that field of view would be sufficient in most virtual reality systems for common tests such as 24–2 or 30–2. For low vision, we expected that field of view at 2× and 4× would be much less than marketed values (70 to 101°) and similar to telescopic devices (e.g., Ocutech Sightscope [Ocutech Inc., Chapel Hill, NC] 2.2× at 18° [monocular] and VES Sport [Ocutech, Chapel Hill, NC] 4× at 12.5°).[15] For convergence therapy, we expected that headsets with longer eye-to-screen distances may not be able to produce sufficient maximum convergence demand (36Δ), especially for patients with smaller interpupillary distances such as children.

METHODS

Six virtual reality systems were selected for measurement: two standalone virtual reality systems and four smartphone virtual reality headsets. Oculus Rift DK2 (development kit 2) and HTC Vive were the two standalone virtual reality systems selected in this study. The Oculus Rift DK2 was selected because of its use in prior amblyopia trials and as a commercially available amblyopia treatment product (Vivid Vision, Vivid Vision Inc., San Francisco, CA).[5] New versions of both the Rift (Rift CV1) and Vive (Vive Pro) with higher pixels per inch (ppi) were available, and minimum angle of resolution was calculated for these using the physical dimensions of the base versions (Table 1) that were accessible for measurements.[16–20] Since data collection, HTC released the Vive Cosmos, which has a 615 ppi display with reported 110° field of view, same as the Vive Pro.[21] Oculus released the Rift CV1 and Quest, which have similar display characteristics.[22]

Commercially available smartphone virtual reality headsets were also selected including Zeiss VR1 (ZEISS, Oberkochen, Germany) and Samsung Gear VR because of their relative quality and well-known name brand and use of the latter for some of the aforementioned products.[23] The Zeiss VR1 and Gear VR official specification sheets reported a fairly wide field of view (101 and 100°, respectively) and therefore were expected to have a shorter eye-to-screen distance. To contrast this, two low-cost virtual reality headsets that seemed to have a relatively long eye-to-screen distance were selected: the SunnyPeak VR headset (purchased on Amazon, Seattle, WA) and VR Box (WOW Virtual Reality, Los Angeles, CA; also available on Amazon). The VR Box is widely available with the same design marketed under various labels (e.g., Hover Way and VR OCT Walmart, Bentonville, AR). Four commercially available smartphones with the highest pixels per inch displays (June 2018) were selected and paired with the virtual reality headsets. This included the Samsung Galaxy S7 and S8, iPhone X (Apple Inc., Cupertino, CA), and LG V30 (LG Electronics Inc., Seoul, South Korea; see Table 1 for the pixels per inch values of each device).[23–25]

Method of Minimum Angle of Resolution Measurement for Virtual Reality Headset Systems

Measurements were made for the screen-to-anterior-cornea distance (eyes closed) after removal of the virtual reality headset lens and display (three authors measured each other). The display could not be removed from the Rift or Vive, and so moldable magnetic beads were placed between the display and the eye (lens removed), adjusted until lightly touching the surface of the lid creating a mold of the eye to screen volume and then measured. To account for the additional distance from the cornea to the entrance pupil, 3 mm was added to the measurement.[26] Thickness of the eyelid was considered to be negligible. The screen-to-entrance-pupil distance and the physical pixel size were used to calculate the angular resolution of each virtual reality system.[27]

$$MAR = \tan^{-1}\left(\frac{p}{d}\right)$$

where p is the physical pixel size (derived from display pixels per inch value); d, screen-to-entrance-pupil distance; and MAR, minimum angle of resolution of the display.

The minimum angle of resolution was converted to Snellen equivalent

$$\frac{20}{1'} = \frac{x}{MAR'}$$

1′ is the minutes of arc subtended by 1 bar (1/2 cycle) in a 20/20 letter (20 in the equation), MAR′ is the minimum angle of

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TABLE 1. Measurements for Oculus Rift, HTC Vive, and VR headset/smartphone pairings

Phone/display	ppi	Headset	Front curve (m)	Back curve (m)	Center thickness (m)	Screen to entrance pupil (mm)	Lens power (D)	MAR 1/2 cycle, 1 pixel (arcmin)	SE (20/x)	logMAR	FOV (°)	2.2× FOV (°)	4× FOV (°)
Oculus Rift DK2	386	Oculus	0.015	–0.22	0.0151	58.13 ± 2.5	35.08	3.90	78	0.59	54.6	24.8	13.7
HTC Vive	448	HTC	0.0416*	–0.11	0.0081	57.68 ± 1.1	28.18	3.37	66	0.52	55.0	25.0	13.8
Oculus Rift CV1†	461	Oculus	—	—	—	—		3.26	65	0.51	54.6	24.8	13.7
HTC Vive Pro†	615	HTC	—	—	—	—		2.46	49	0.39	55.0	25.0	13.8
Samsung S8	570	SunnyPeak	0.078	–0.08	0.0049	75.86 ± 2.9	12.75	2.01	40	0.30	47.2	21.5	11.8
iPhone X	458	SunnyPeak	0.078	–0.08	0.0049	75.86 ± 2.9	12.75	2.49	50	0.39	47.6	21.6	11.9
LG V30	538	SunnyPeak	0.078	–0.08	0.0049	75.86 ± 2.9	12.75	2.13	42	0.32	48.4	22.0	12.1
Samsung S7	577	SunnyPeak	0.078	–0.08	0.0049	75.86 ± 2.9	12.75	1.98	40	0.29	40.8	18.5	10.2
Samsung S8	570	Zeiss VR1	0.017	–0.04	0.0142	58.97 ± 2.5	30.76	2.60	52	0.41	53.9	24.5	13.5
iPhone X	458	Zeiss VR1	0.017	–0.04	0.0142	58.97 ± 2.5	30.76	3.23	65	0.51	53.9	24.5	13.5
LG V30	538	Zeiss VR1	0.017	–0.04	0.0142	58.97 ± 2.5	30.76	2.76	55	0.44	53.9	24.5	13.5
Samsung S7	577	Zeiss VR1	0.017	–0.04	0.0142	58.97 ± 2.5	30.76	2.56	51	0.41	53.9	24.5	13.5
Samsung S8	570	Gear VR	0.018	–0.07	0.0115	59.19 ± 2.6	29.25	2.58	52	0.41	53.8	24.5	13.5
iPhone X	458	Gear VR	0.018	–0.07	0.0115	59.19 ± 2.6	29.25	3.22	64	0.51	53.8	24.5	13.5
LG V30	538	Gear VR	0.018	–0.07	0.0115	59.19 ± 2.6	29.25	2.74	55	0.44	53.8	24.5	13.5
Samsung S7	577	Gear VR	0.018	–0.07	0.0115	59.19 ± 2.6	29.25	2.55	51	0.41	53.8	24.5	13.5
Samsung S8	570	VR Box	0.036	–0.15	0.0075	78.41 ± 1.1	14.67	1.95	39	0.29	45.8	20.8	11.5
iPhone X	458	VR Box	0.036	–0.15	0.0075	78.41 ± 1.1	14.67	2.40	49	0.39	46.2	21.0	11.6
LG V30	538	VR Box	0.036	–0.15	0.0075	78.41 ± 1.1	14.67	2.07	42	0.32	47.0	21.4	11.8
Samsung S7	577	VR Box	0.036	–0.15	0.0075	78.41 ± 1.1	14.67	1.91	39	0.28	39.6	18.0	9.9
Mean ± SD	507 ± 74		0.033 ± 0.024	–0.11 ± 0.06	0.0102 ± 0.0037	64.71 ± 8.83	25.12 ± 8.36	2.61 ± 0.54	51	0.41 ± 0.09	50.2 ± 4.8	23.0 ± 2.2	12.7 ± 1.2

Lens curvatures were made with a lens clock, lens thickness with a lens thickness gauge, screen to eye with a millimeter rule, and lens power with an autolensometer (see the Methods section for more details). All measurements were taken three times and averaged. Pixels per inch were obtained from the manufacturer, and MAR and Snellen equivalents were calculated. *Hybrid diffractive lens. †Upgraded versions of the virtual reality systems for which computations were made assuming dimensions of the corresponding base versions. FOV = field of view; MAR = minimum angle of resolution; ppi = pixels per inch; SE = Snellen equivalent.

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resolution of the display in arc minutes, and x is the Snellen equivalent of the MAR′. The MAR′ was also converted to logMAR by taking the $\log_{10}$.

Field of View Measurements

Field of view was calculated for each headset and phone combination using the measured screen-to-entrance-pupil distance. In all headsets, the limiting factor for the nasal visual field was the septum at the center of the screen (not the lens diameter). All headsets had a septum at the midscreen point to prevent the right eye from seeing the left eye image and vice versa. This septum sat directly between the eyes, and therefore, its position was equivalent to the monocular interpupillary distance at far. Therefore, the nasal field of view was calculated as the arc tangent of the monocular interpupillary distance at far over the screen-to-entrance-pupil distance.

$$FOVn = \tan^{-1}\left(\frac{IPDm}{d}\right)$$

where IPDm is the monocular interpupillary distance at far; d, screen-to-entrance-pupil distance; and FOVn, horizontal nasal field of view of the display.

For the horizontal temporal field, for most displays/phones, the limiting factor was the visible monocular horizontal screen size (when in the virtual reality headset), which in most headset models was limited by the aperture between the lens and the display (i.e., part of the phone display was blocked).

$$FOVt = \tan^{-1}\left(\frac{S-IPDm}{d}\right)$$

where S is the monocular horizontal screen size; IPDm, the monocular interpupillary distance at far; d, screen-to-entrance-pupil distance; and FOVt, temporal field of view of the display.

The exception was the Sunnypeak where the housing aperture was not fixed and could be expanded to accept larger phones. In this case, the temporal edge of the field was defined by the horizontal display size for each phone type.

The field of view calculations were empirically verified in a Goldmann perimeter for the right eye of one author (SP) using a V4e kinetic stimulus for four of the virtual reality headsets. The HTC Vive and Gear VR were not measured in the perimeter because the front of the headset could not be removed without breaking it apart. For the other four headsets, the right lens was removed for the perimetry test and the forehead rest was removed in the perimeter (chinrest left in place) to allow for proper placement of the head with the virtual reality headset. To consider use of the virtual reality headsets for convergence training, we calculated the maximum convergence demand that could be generated in each headset as it varied by interpupillary distance. In our calculations, we accounted for the 40-cm vergence demand and left a 10° buffer (α) to allow for space for the nasal macula with the rationale that loss of this area would interfere with normal fusional mechanisms. Manufacturers will be able to calculate the vergence demand for any distance by changing the working distance of interest. The equation used for maximum possible vergence demand is then expressed as follows:

$$Max\ Convergence = 2*100*\tan(FOVn-\alpha-NVD)$$

where Max Convergence is the prism diopters (Δ) of vergence of both eyes combined that can be generated for a 40-cm equivalent viewing distance; *2 is to double values to account for the fact that this amount of vergence demand is generated for each eye; 100 is the prism diopter conversion; FOVn is the nasal field of view of the headset for that patient calculated as $\tan^{-1}\left(\frac{mIPD}{d}\right)$, where mIPD is the monocular interpupillary distance at far (measured for the patient with, e.g., pupilometer) and d is the head-mounted display-to-eye nodal point distance (measured for the headset of interest using methods described earlier); and NVD is the desired near vergence demand calculated as $\tan^{-1}\left(\frac{IPDm}{WD}\right)$, with WD being the desired near working distance (typical is 40 cm). See example. Please note that the near interpupillary distance should not be used in this calculation, even though near demand is desired.

Example: A patient measured to have a monocular interpupillary distance at far of 35 mm is using a SunnyPeak headset, which measured as having a screen-to-nodal point d of 75.85 mm.
Step 1: Calculate $FOVn = \tan^{-1}\frac{35}{75.85} = 24.77°$.
Step 2: Calculate the near vergence demand at 40 cm, $\tan^{-1}\frac{35}{400} = 5.0°$.
Step 3: Subtract the 5° from step 2 and 10° (α); for the nasal macula = 24.77° − (5° + 10°) = 9.77°.
Step 4: Convert this to prism diopters (Δ).
100 (tan (9.77°)) = 17.23Δ
Finally, multiply this by 2 to account for this demand generated in each eye = 34.44Δ.
The maximum near convergence demand that can be generated in the SunnyPeak headset for this patient is 34.44Δ.

There may be concern that mismatch between user interpupillary distance and virtual reality headset lens interpupillary distance would create large amounts of prismatic effect; however, this is not the case. Only the power of the lens in excess of what is needed to bring the optical image of the screen to infinity participates in the decentration-induced prismatic effect, and therefore, prismatic effect in the virtual reality headset based on decentration is small[26] but could be seen when adjusting lenses in the headsets with adjustable eyepieces. A study comparing phoria and vergence measures in head-mounted display versus phoropter is needed to determine if these horizontal prismatic effects are clinically significant (~2Δ). Similarly, magnification effects of the headset lens relative to calculating magnification factors for low vision use should be minimal.

To consider the field of view for 2× and 4× low vision applications, the empirically verified calculated mean monocular horizontal field of view was divided by 2 and 4.

Other Virtual Reality Headset Measurements

The lens characteristics were also measured for each virtual reality headset. All measurements were taken three times and averaged. Front and back base curves were measured with a lens clock (Hilco, Plainville, MA), lens thickness with a lens thickness gauge (Western Ophthalmics, Lynnwood, WA), and lens back vertex power with a Topcon CL-100 auto-lensometer (Topcon, Tokyo, Japan), which had a range of ±20 D. When the virtual reality headset lens was above the range of the lensometer, a minus trial lens was placed between the flatter back curve of the lens to be measured and the lensometer objective lens/lens stop, and then the absolute value was added to the lensometer reading. Although lensometer is not the ideal method for measuring a thick lens, this approach is widely available to clinicians and provides some repeatable reference to consider the findings. We felt this would be more valuable to the clinical community than optical bench measurements. We also provide lens thickness and curvature so that

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those interested in a more precise calculation of the back vertex power would be able to use these data.

To predict the display resolution needs and/or headset eye-to-screen distance for optimal amblyopia treatment and visual acuity testing (considered to be an ability to display 0.0 logMAR [20/20]), calculations were done with the aforementioned equations while varying either the pixels per inch or eye-to-screen distance (*d*). The functions were then plotted as logMAR versus pixels per inch and (*d*), respectively. Pixels per inch were varied from 270 to 2228 to allowing the reader to reference back to older phone models with lower pixels per inch (e.g., iPhone 4 had pixels per inch of 326). The upper range (2228) was assigned to bring all headsets to 20/15 or better (plus a buffer) and does not represent any existing or planned display technology, and (*d*) was varied from 59 (lowest eye-to-screen distance presently available) to 287 mm (brought all headsets to 20/15 or better). A virtual reality headset minimum angle of resolution and field of view calculator is provided in Appendix Figure A1 (available at http://links.lww.com/OPX/A451).

RESULTS

Minimum Angular Resolution in logMAR

Fig. 1 details the at-scale schematics for each virtual reality headset. All measurements and calculations are provided in Table 1, including lens thickness, screen-to-entrance-pupil distance, lens power, minimum angular resolution in logMAR, and 20-ft Snellen equivalents. Field of view represents the mean for different phone types in each smartphone headset, which varied slightly with phone screen size when the temporal edge was not obscured by the headset housing.

Minimum angular resolution in logMAR ranged from 0.28 (20/39) in the VR Box with Galaxy S7 phone to 0.59 (20/78) in the DK2, with a mean of 0.41 ± 0.09 (20/51). Higher-resolution smartphones (Samsung Galaxy S7 with 577 ppi and Samsung Galaxy S8 with 570 ppi) paired with the virtual reality headsets with greater eye-to-screen distances (SunnyPeak at 75.86 ± 2.9 mm and VR Box at 78.41 ± 1.1 mm) resulted in the pairings with the best resolutions, also shown in Fig. 2. Eye-to-screen measurements for the other systems were 58.13 ± 2.5 mm for Rift, 58.97 ± 2.5 mm for Zeiss, 59.19 ± 2.6 mm for Gear, and 57.68 ± 1.1 mm for Vive.

Field of View

The field of view of the headsets can be calculated using the measured eye-to-screen distance and the visible areas of the display. To verify the calculations, field of view was empirically measured in a Goldmann perimeter for one of the authors (SP) and compared with their calculated field of view. The Goldmann-measured horizontal field of view closely matched the calculated values for the SunnyPeak with 43° (calculated[a]) and 41° (perimeter), and VR Box 41° (calculated) and 42° (perimeter). Plots are available in Appendix Figure A2 (available at http://links.lww.com/OPX/A451). The Gear VR and VR1 showed a slight discrepancy with 52° (calculated) and 47° (perimeter) for the Gear VR, and 52° and 48° for the VR1. Given the discrepancy, a post hoc evaluation was performed where perimetry was repeated using a different methodology. A piece of paper was placed into the virtual reality headset, a light source was diffused by the paper, and a mark was placed at the point perceived as straight ahead of the eye on the paper serving as a fixation point. Next, a pencil tip was used to kinetically map the edge of the field (nonseeing to seeing) onto the paper in the goggle (pencil tip could be seen through the paper as a shadow). The linear extent (in millimeters) from the fixation point to the nasal and temporal field edge was measured, and the screen-to-entrance-pupil distances were used (for the corresponding virtual reality headset) to calculate the angular field of view. With this method, there were no discrepancies for Gear VR (52° calculated, 51° perimetry) or the VR1 (52° calculated, 51° perimetry). These findings were taken to empirically verify the calculated field of view, which can therefore be used to compare all the devices.

The average field of view for each phone/headset combination is reported in Table 1 (calculated based on the average screen-to-entrance-pupil distance for the three authors). The largest horizontal field of view was 55.0° for the HTC Vive and Vive Pro, followed closely by the Rift DK2 and CV1 at 54.6°. The smallest was the VR Box combined with the Galaxy S7 phone at 39.6°.

Maximum Convergence Demand

The nasal field of view is the limiting factor when attempting to generate convergence demand. The nasal field was limited by the headset septum (not the lens) and therefore shrinks with the interpupillary distance and with greater eye-to-screen distance (Fig. 4). Therefore, the HTC Vive, which had the shortest eye-to-screen distance, also allowed the greatest binocular convergence demand ranging from 22.0Δ if the patient were, for example, a child with a very small interpupillary distance of 40 mm up to 58.0Δ if the patient were to have a very large interpupillary distance of 70 mm. The poorest option for generating convergence demand was by the VR Box, which only allowed 5.1Δ for an interpupillary distance of 40 mm to 31.9Δ for an interpupillary distance of 70 mm. The mean maximum convergence demand of all headsets for a 60-mm interpupillary distance was 38.6 ± 10.1Δ. Four headsets could meet the benchmark of 36Δ (Zeiss, Gear VR, Vive, and Rift), with the mean minimum interpupillary distance where this benchmark could be met being 58.5 ± 0.6 mm.

Fig. 3A shows theoretical calculations of the necessary pixels per inch to achieve specific logMAR (left-side *y* axis) and 20-ft Snellen equivalents (right-side *y* axis). The required display pixel density for each virtual reality headset to achieve logMAR equivalent of 20/20 (logMAR 0.0) is as follows: Oculus Rift DK2, 1500 ppi; HTC Vive, 1510 ppi; SunnyPeak, 1138 ppi; VR Box, 1108 ppi; Gear VR, 1468 ppi; and Zeiss VR1, 1478 ppi. For the standalone virtual reality systems, the Oculus Rift DK2 (386 ppi) and the HTC Vive (456 ppi), Fig. 3B also illustrates that the required eye-to-screen distance to reach 20/20 (0.0 logMAR) is around 15 cm when using the highest-resolution (Samsung S7) display. The convergence at near would at least need to reach the norm of 36Δ, and therefore, a mean binocular interpupillary distance at far of 58.5 mm (mean of the four headsets that reached 36Δ) or larger would be needed.

Fig. 4 shows theoretical calculations of the change in the maximum convergence demand that can be generated when varying interpupillary distance by virtual reality headset. The VR Box and Sunnypeak are separated from the other headsets (data line lower on the plot) as being inferior for convergence testing and training.

Low Vision Applications

Given that the field of view of the Gear VR was calculated at 53.8° (used for the Patriot ViewPoint, IrisVision, and Relumino

[a]This calculated value does not match those in Table 1 because only SP sat for perimetry, whereas those in Table 1 are a calculated average for the 3 authors and are limited by the horizontal dimension of the phone used.

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[Samsung, Suwon, South Korea] low vision aids), the field of view at 2.2× can be calculated as 24.5 and 13.5° at 4×, comparable to spectacle-mounted bioptic telescope aids such as the Ocutech Sightscope 2.2× at 18° (monocular) and VES Sport 4× at 12.5°. The means of all headsets were 25.1 ± 2.2 and 12.5 ± 1.2° for 2.2× and 4× respectively.

DISCUSSION

This is the first study to perform detailed measurements of common (at the time of this publication) virtual reality headsets in the interest of better understanding their potential application for

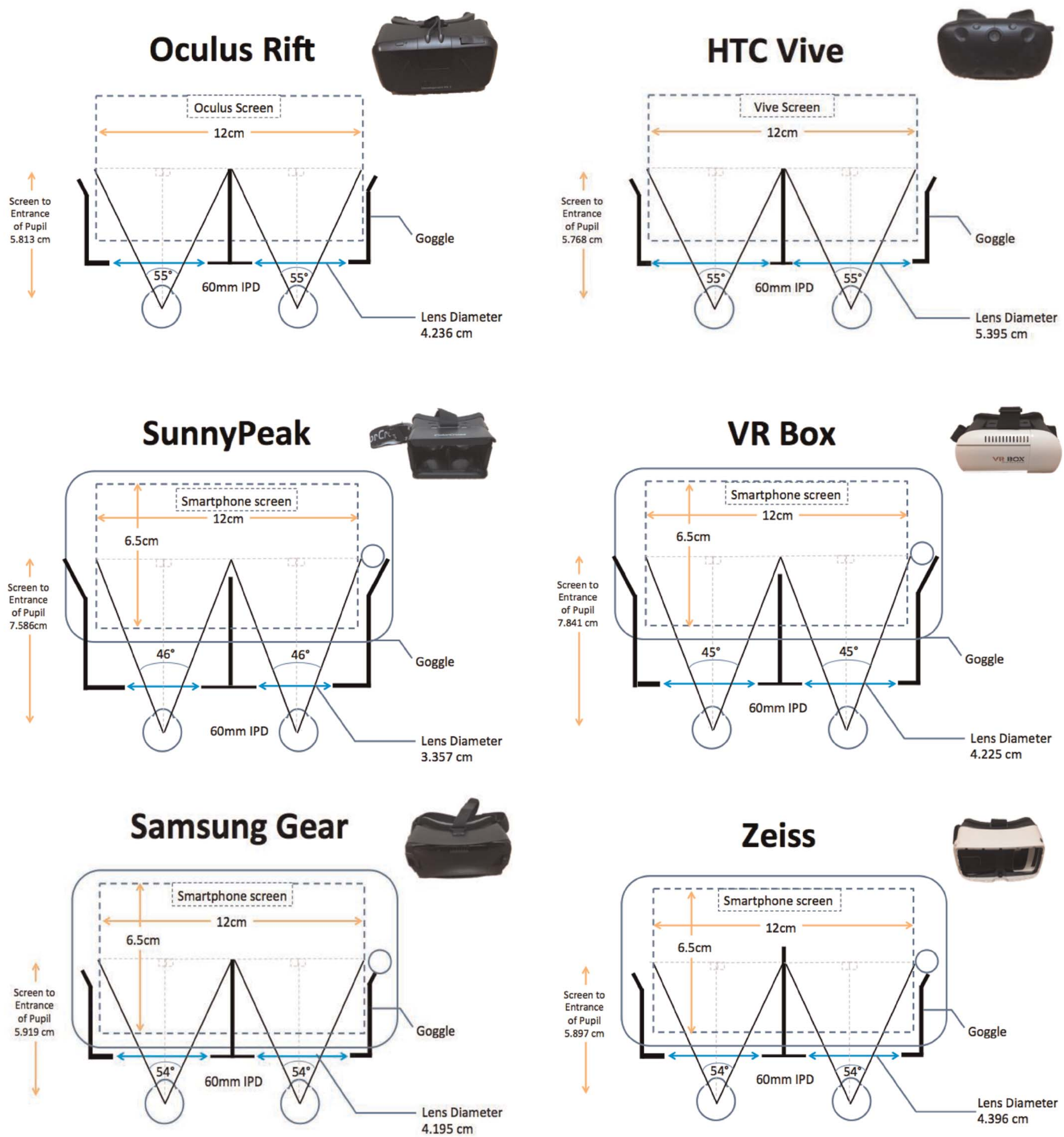

FIGURE 1. Schematics of virtual reality headset options drawn to scale and viewed from above. The headsets with dedicated internal displays, Oculus Rift and HTC Vive, are on the top row; SunnyPeak and VR Box with longer eye-to-screen distances are in the middle row; and Zeiss and Samsung Gear with shorter eye-to-screen distances are shown on the bottom row.

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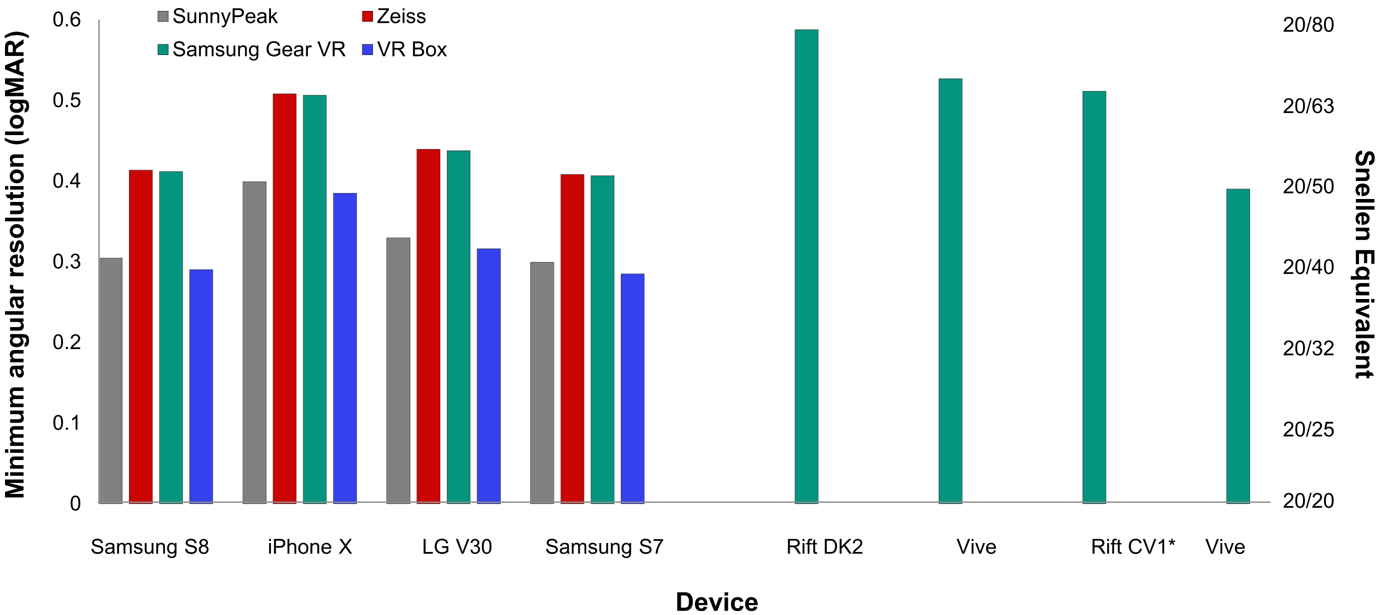

FIGURE 2. Logarithm of minimum angular resolution (logMAR) measured for standalone virtual reality headsets (Rift and Vive) and for various virtual reality headset/smartphone pairings. The corresponding Snellen denominator is shown on the right side of the chart. The minimum angular resolution in logMAR ranged from 0.28 (20/39) in the VR Box with Galaxy S7 phone to 0.59 (20/78) in the DK2, with a mean of 0.41 ± 0.09 (20/51). Higher-resolution smartphones (Samsung Galaxy S7 with 577 pixels per inch [ppi] and Samsung Galaxy S8 with 570 ppi) paired with the virtual reality headsets with greater eye-to-screen distances (SunnyPeak at 75.86 ± 2.9 mm and VR Box at 78.41 ± 1.1 mm) resulted in the pairings with the best resolutions. Minimum angle of resolution is calculated for Rift CV1 and Vive Pro with larger ppi, but assuming other specifications are similar to the Rift DK2 and Vive, respectively (hence, indicated by an *).

vision testing, therapy, and low vision applications. In addition to the eye-to-display distance, we provide lens characteristics not provided by the manufacturers, which should be helpful to the optometric and ophthalmologic clinical and research communities. A primary finding of this study is that the mean log minimum angular resolution (logMAR) of systems tested was 0.41 (20/51), and no virtual reality products currently available or marketed for amblyopia treatment reach logMAR 0.0 (20/20). This is a problem for acuity testing and possibly for amblyopia therapy, assuming the goal acuity is better than 20/40 and that these higher resolutions are needed for treatment success. Prior studies support the assertion that improvement in acuity requires use of high-resolution information in the form of a discrimination task.[28] Even with the possibility of Japan Display Inc.'s new 1001 ppi LCD, the goal target 20/20 will be out of reach (Fig. 3).[29]

Another important finding is that the manufacturer-reported field of view is incorrect. It seems the sum of the monocular fields of each eye is being reported; however, this is not appropriate because during virtual reality gaming and movie watching, the monocular fields are largely overlapping. Areas of the temporal field are not overlapping for some users with smaller interpupillary distances, but in most headsets, this does not give additional temporal field of view because of the boundaries of the headset enclosure. When the monocular interpupillary distance at far is equal to the display horizontal dimension, which was ~60 mm in most headsets (Fig. 1), the monocular field of view is equal to the binocular field of view, 60 mm is close to the population norm of 63 mm,[30] and so reporting the monocular field of view as the field of view of the device in specification sheets would be the most appropriate method.

The virtual reality headsets provide reasonable field of view for many types of visual field testing. For example, a 24–2 or 30–2, which require a total of 48 and 60° could be accomplished for any of the headsets by shifting the fixation point (e.g., to the temporal side when testing the nasal field). The amount of aberration from the headset lens is not insignificant and would need to be studied to determine how to correct for this when measuring field sensitivity.

Near convergence testing requires a much greater degree of image displacement compared with distance testing, and so is the limiting factor for the virtual reality headsets in testing vergence ranges. Four of the virtual reality headsets provided enough field of view for near convergence testing and training for patients with binocular interpupillary distance at far greater than 58 mm. The normal convergence break point at 40 cm with Risley prisms has been reported as 21Δ, and when accounting for the 40-cm vergence, demand would be 36Δ (18Δ in each eye).[13] Therefore, the Gear VR, VR1, Rift, and Vive should be sufficient for convergence testing or training in patients with binocular distance interpupillary distance greater than 58 mm (Fig. 4). Unfortunately, the VR Box and Sunnypeak could not measure or train to the 36Δ benchmark for any reasonable interpupillary distance. In terms of binocular vision vergence range testing, virtual reality headsets with smaller fields of view would be quite limited to capture the full population range of convergence break point but could still catch abnormally low convergence ranges, and so may have some use in screening. It is possible that normal vergence ranges in virtual reality headsets will be different from those in benchmark Risley prism testing

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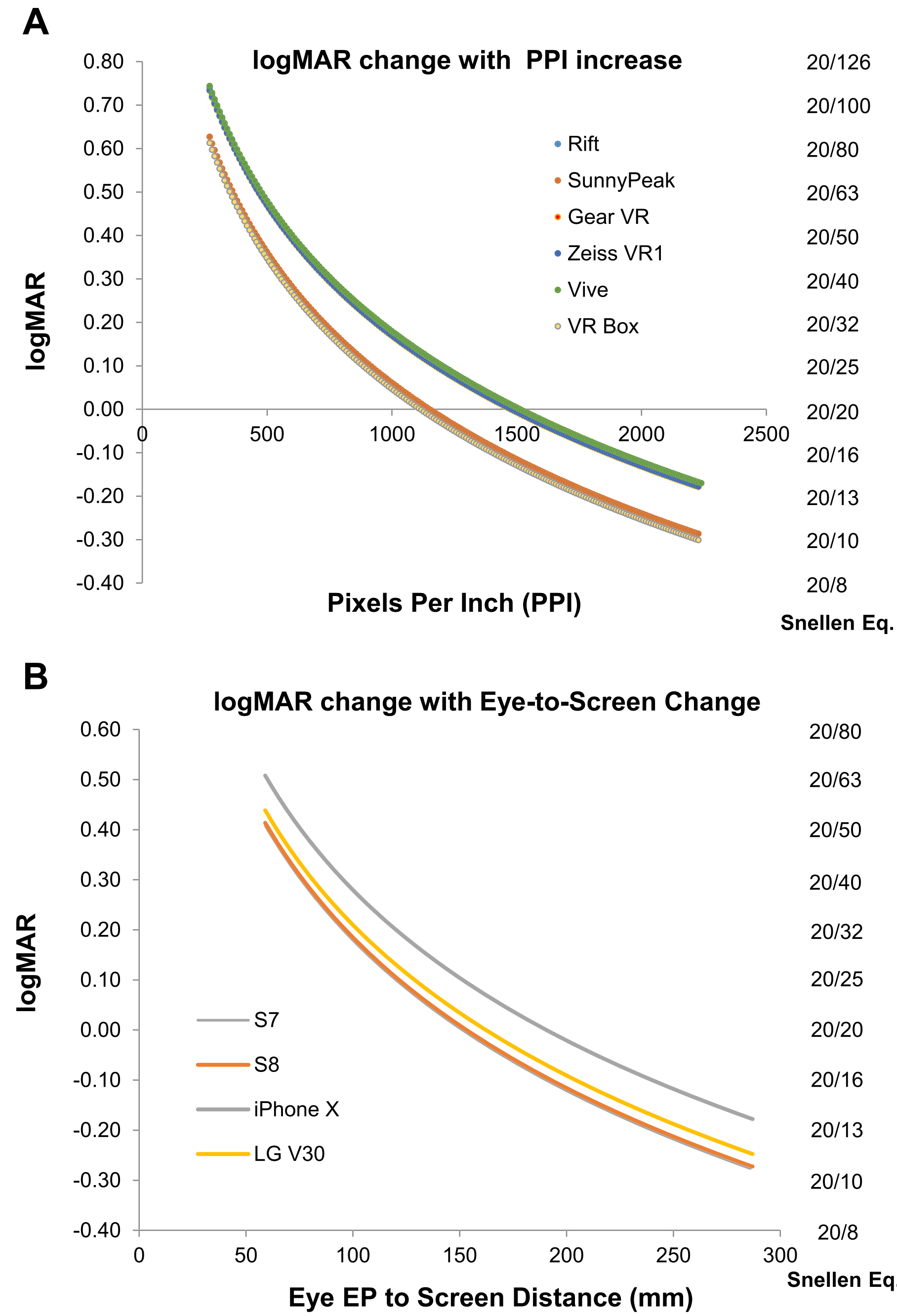

FIGURE 3. (A) Theoretical calculations of the necessary pixels per inch (ppi) to achieve specific minimum angular resolution in logMAR (left-side *y* axis) and 20-ft Snellen equivalents (right-side *y* axis). The required display pixel density for each VR headset to achieve logMAR equivalent of 20/20 (logMAR 0.0) is as follows: Oculus Rift DK2 1500 ppi, HTC Vive 1510 ppi, SunnyPeak 1138 ppi, VR Box 1108 ppi, Gear VR 1468 ppi, and Zeiss VR1 1478 ppi. For the standalone virtual reality systems, the Oculus Rift DK2 (386 ppi), and the HTC Vive (456 ppi), (B) the required eye-to-screen distance to reach 20/20 (0.0 logMAR) is around 15 cm when using the highest-resolution (Samsung S7) display. The convergence at near would at least need to reach the norm of 36Δ, and therefore, a mean binocular interpupillary distance at far of 58.5 mm (mean of the four headsets that reached 36Δ) or larger would be needed.

because of accommodative demand being zero rather than +2.50 D. This might be addressed by having the user wear a −2.50 D clip over their distance glasses during use for users younger than 40 years. Older patients would need to use the difference between their spectacle add and −2.50 D (e.g., those with a +1.50 D add would get a −1.00 D clip). Adjusting the refractive error correction slider on virtual reality headsets that have this option (e.g., VR Box and SunnyPeak) could also potentially address this issue, but it is difficult to have precise control and so is not recommended. The effect of headset lens distortion could be compensated digitally, as is done for virtual reality content.

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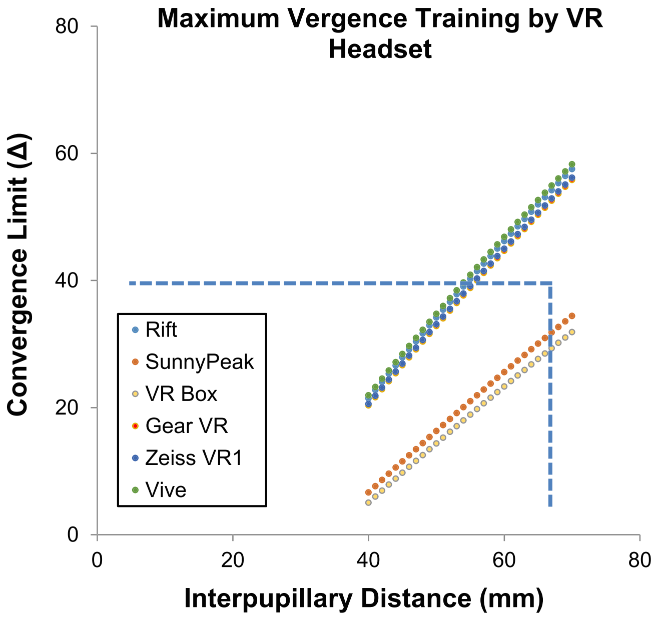

FIGURE 4. Theoretical calculations of the change in the maximum convergence demand that can be generated varying by interpupillary distance by virtual reality headset. The VR Box and Sunnypeak are separated from the other headsets (data line lower on the plot) as being inferior for convergence testing and training. The convergence at near would at least need to reach the population norm of 36Δ (blue dashed line), and therefore, a mean binocular interpupillary distance at far of 58.5 mm (mean of the four headsets that reached 36Δ) or larger would be needed. *Upgraded versions of the virtual reality systems for which computations were made assuming dimensions of the corresponding base versions. [a]Hybrid diffractive lens.

For low vision virtual reality headset products, field of view reporting by manufacturers is incorrect and misleading. The Gear VR headset is the most common for low vision products (Patriot ViewPoint, IrisVision, Relumino). At 2.2× and 4× magnification, the field of view of these devices will be 24.5 and 13.5°, much closer to spectacle-mounted optical telescopes such as Ocutech Sightscope 2.2× at 18° (monocular) and VES Sport 4× at 12.5° than the marketed 70 and 101°.

The current virtual reality headsets have been manufactured by focusing on the needs of the gaming and virtual reality community, which has been the primary driving force behind the development of this technology. To better suit consumer needs, the virtual reality headsets over time have used increasingly powerful and more complex optics, which has allowed them to shrink the depth of the headset and make it more compact giving a larger field of view at the cost of angular resolution. Display pixel densities have also improved, but not to a point where these improvements would counteract the progressive lowering of the virtual reality headset dimensions. Although it is possible that headsets could be fabricated specifically with particular clinical applications in mind, it cancels the benefit of building on existing technology and does not seem imminent in the near future. Thus, it is important to understand the limitations of the current virtual reality technology with regard to the minimum angle of resolution when adopting it for amblyopia treatment and monitoring or other visual testing applications, particularly for visual acuity. Visual field, vergence testing/training, and low vision magnification require an opposite approach, optimizing the field of view with the angular resolution being less important, and so different virtual reality headsets would be the best solution at this time. It is somewhat cumbersome (and more expensive) to have multiple headsets, and this may influence the feasibility of the technology. The impact of the high plus lens via aberration for acuity and threshold field applications is another consideration, which is beyond the scope of this study but is important before the clinical deployment of such technologies.

Although we expect that our sample of virtual reality headsets was representative, there may be headsets not included in this study with marginally higher angular resolution due to a longer eye-to-screen distance. We do not expect there are designs with much greater eye-to-screen distance given that the weight and added bulk would make the headsets uncomfortable and unwieldy. The study was not designed or intended to determine the effect of virtual reality systems on amblyopia and/or convergence insufficiency, and patients were not tested with the various systems. It is possible that visual acuity in amblyopia treatment might improve beyond the minimum angle of resolution of the virtual reality system from reduced suppression because of the presence of higher spatial frequencies in most images. Images that are not of repeating patterns, for instance, an image including only a single edge or natural images, can be typically decomposed into a wide band of signals from low to high frequencies by Fourier transform. Those high spatial frequencies are presented to the visual system despite the whole image being displayed on a low-resolution display and stimulate the neurons tuned for high spatial frequencies.[31] Thus, it is possible the amblyopia treatment does not require training tasks at the goal spatial frequency, and the mere presence of high spatial frequencies is sufficient, but this hypothesis would need to be tested before recommending the technology for standalone amblyopia care. Our recommendation is that clinicians might use virtual reality amblyopia systems such as Vivid Vision and other emerging products as an adjunct to traditional amblyopia treatments, primarily for antisuppression therapy, for which the 20/40 to 20/70 range of resolution may be sufficient, but additional studies should be done to confirm. The added value of antisuppression therapy for amblyopia is yet to be confirmed with mixed results in prior studies.[32–34]

Despite the possible limitation in resolution, virtual reality systems offer great promise for amblyopia treatment and for other vision care applications by motivating and engaging patients and thereby potentially enhancing compliance. It seems likely that the market for virtual reality gaming and movies will continue to drive improvements in resolution and field of view, and this study provides a reference by which to gauge the improvements for their applicability for vision care.

CONCLUSIONS

Current virtual reality technologies have limitations to angular resolution and field of view that should be closely evaluated before clinical implementation. Future projects that work to enhance the application of virtual reality in vision therapy, magnification for low vision, and vision testing should consider these limitations and how they might impact outcomes. In addition, as more virtual reality headsets become commercially available and potentially used in vision care, it is important to empirically verify these values as they are likely to directly impact care provided to patients.

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ARTICLE INFORMATION

Supplemental Digital Content: Appendix Figure A1: Sample virtual reality headset minimum angle of resolution and field of view calculator created by the authors is available at http://links.lww.com/OPX/A451.

Appendix Figure A2 (available at http://links.lww.com/OPX/A451): The field of view of the headsets can be calculated using the measured eye-to-screen distance and the visible areas of the display. To verify the calculations, field of view was empirically measured in a Goldmann perimeter for one of the authors (SP) and compared with their calculated field of view. The Goldmann-measured horizontal field of view closely matched the calculated values for the SunnyPeak with 43° (calculated) and 41° (perimeter), and VR Box 41° (calculated) and 42° (perimeter).

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