tvst

Pediatric Ophthalmology & Strabismus

Quotidian Profile of Vergence Angle in Ambulatory Subjects Monitored With Wearable Eye Tracking Glasses

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Received: November 4, 2022
Accepted: January 17, 2023
Published: February 13, 2023

Keywords: pupil; ductions; strabismus; convergence insufficiency; interpupillary distance; tobii pro glasses 3

Citation: Dilbeck MD, Gentry TN, Economides JR, Horton JC. Quotidian profile of vergence angle in ambulatory subjects monitored with wearable eye tracking glasses. Transl Vis Sci Technol. 2023;12(2):17, https://doi.org/10.1167/tvst.12.2.17

Purpose: Wearable eye trackers record gaze position as ambulatory subjects navigate their environment. Tobii Pro Glasses 3 were tested to assess their accuracy and precision in the measurement of vergence angle.

Methods: Four subjects wore the eye tracking glasses, with their head stabilized, while fixating at a series of distances corresponding to vergence demands of: 0.25, 0.50, 1, 2, 4, 8, 16, and 32°. After these laboratory trials were completed, 10 subjects wore the glasses for a prolonged period while carrying out their customary daily pursuits. A vergence profile was compiled for each subject and compared with interpupillary distance.

Results: In the laboratory, the eye tracking glasses were comparable in accuracy to remote video eye trackers, outputting a mean vergence value within 1° of demand at all angles except 32°. In ambulatory subjects, the glasses were less accurate, due to tracking interruptions and measurement errors, partly mitigated by the application of data filters. Nonetheless, a useful record of vergence behavior was obtained in every subject. Vergence profiles often had a bimodal distribution, reflecting a preponderance of activities at near (mobile phone and computer) or far (driving and walking). As expected, vergence angle correlated with interpupillary distance.

Conclusions: Wearable eye tracking glasses make it possible to compile a nearly continuous record of vergence angle over hours, which can be correlated with the corresponding visual scene viewed by ambulatory subjects.

Translational Relevance: This technology provides new insight into the diversity of human ocular motor behavior and may become useful for the diagnosis of disorders that affect vergence function such as: convergence insufficiency, Parkinson disease, and strabismus.

Introduction

Vergence eye movements rotate the globes in opposite directions to align the foveae on visual targets located at a range of distances from the observer.[1] They often incorporate changes in gaze direction, generating complex eye movements that combine saccades with shifts in vergence angle.[2–4] Although such eye movements have been studied intensively in the laboratory, less is known about ocular motor behavior while humans freely navigate their visual environment in the course of normal daily life.[5,6]

Many clinical disorders result from impairment of vergence function.[7] In divergence insufficiency, subjects are able to fuse at near, but become exotropic at distance.[8–12] In convergence insufficiency, fusion is intact at distance but a symptomatic exophoria (or even exotropia) emerges at near. This condition occurs in up to 4% of school children.[13,14] It is also common after head trauma or in certain neurodegenerative conditions, such as Parkinson disease.[15–18]

To diagnose vergence disorders and their response to treatment, clinicians typically measure the near point of convergence and document the alignment of the eyes at near and far with a cover test.[19–21] It would be valuable to obtain additional information about the range, accuracy, and prevalence of vergence eye movements to targets located at difference distances. The advent of remote (e.g. desk mounted) video-based eye trackers has made it relatively easy to acquire such data in a laboratory setting.[22] However, the data are usually collected over a relatively brief period and do not reflect vergence behavior while engaged in a repertoire of regular activities.

Eye tracking glasses allow one to record gaze direction of ambulatory subjects moving through their visual environment, as captured by a scene camera. Here, we describe our experience with Tobii Pro Glasses 3 in the measurement of vergence eye movements. The device provides a readout of binocular gaze position, but information about the position of each eye alone is extractable, allowing one to calculate vergence angle.

This study consists of two halves. In the first part, we test the performance of the instrument in a series of laboratory experiments, to define its accuracy and operational characteristics under optimal recording conditions.[23] In the second part, we present data from a cohort of 10 healthy subjects, capturing their eye movements and shifts in vergence angle over many hours of ambulatory recording. Such data were not attainable prior to the invention of wearable eye trackers. They provide the first documentation of human vergence behavior measured during normal activity for long periods. The instrument may permit quantitative assessment of function in patients with disorders of vergence, while the individuals are engaged in the actual visual tasks that present a challenge to them.

Methods

Vergence Angle Measurements

These experiments were conducted with the Tobii Pro Glasses 3 (www.tobiipro.com), a third generation instrument that consists of eye glasses with 8 infrared illuminators and 2 cameras embedded in each plano lens (Fig. 1). The firmware version was 1.231+pumpa and the controller software version was 1.9.4. The device incorporates a scene camera that captures 95° horizontally by 63° vertically with a resolution of 1920 × 1080 pixels at 25 Hz, along with a microphone, accelerometer, gyroscope, and magnetometer. Data are streamed from the glasses via a cable to a recording unit worn by the subject. In the recording unit, the position of each eye relative to the scene is computed at 50 Hz from information about the location of the pupil center and the 8 illuminator reflections on the cornea. The fixation point is overlaid atop the scene camera view and the composite image is viewable via a wireless connection to a tablet, computer, or smartphone. The live view display has a latency of 0.2 seconds. Data are also serialized on a secure digital (SD) card in a variety of file formats: JSON, mp4, and csv.

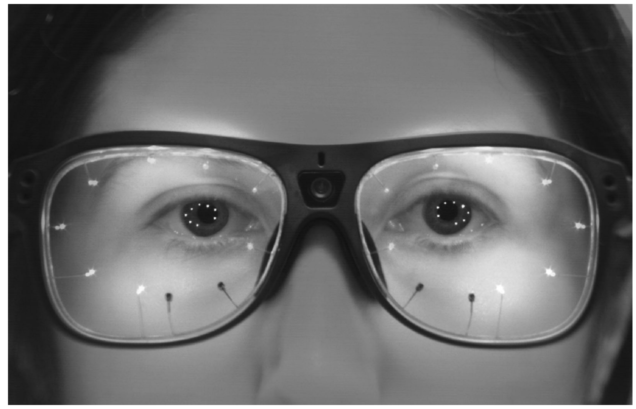

Figure 1. Composite of images taken under infrared and visible light of a subject wearing the Tobii Pro Glasses 3. The device contains eight miniature infrared illuminators and two cameras (inferonasal) embedded in each lens. The eight illuminators are reflected on the cornea in a semi-circular pattern. A camera mounted on the bridge of the glasses captures the scene. A microphone is located just above the camera.

The Tobii Pro Glasses 3 are powered by lithium ion batteries that supply power for 100 minutes. An external rechargeable battery pack was plugged into the recording unit to allow up to 12 hours of operation. Both devices were placed into a lightweight satchel to allow the subject unrestricted mobility. When outdoors, subjects wore a pair of slip-on tinted infrared-blocking lenses. The Tobii Pro Glasses 3 were calibrated by having subjects fixate a bull's eye target held between 50 and 100 cm at eye level.

Using a custom script written in Igor Pro (www.wavemetrics.com), data were extracted from the JSON file containing the three-dimensional spatial coordinates (x, y, and z) that encode the gaze direction of each eye. The horizontal position of the center of gaze for each eye, in degrees relative to the plane of the scene video, was calculated by applying the following functions:

$$Horizontal\ position_{right\ eye} = -\arctan\left(\frac{x_{right\ eye}}{z_{right\ eye}}\right) \times \frac{180^\circ}{\pi}$$

$$Horizontal\ position_{left\ eye} = -\arctan\left(\frac{x_{left\ eye}}{z_{left\ eye}}\right) \times \frac{180^\circ}{\pi}$$

where x is the horizontal coordinate and z is the depth coordinate of the end point of the gaze direction vector. Applying these transformations, horizontal positions to the right are positive.

To calculate vergence, the horizontal position of the right eye was subtracted from the horizontal position of the left eye. Positive values denoted convergence. Histograms were compiled in 0.2° bins to create a "vergence profile," which showed the time that each subject fixated at a given vergence angle.

Interruptions and aberrant points are often present in the data stream from video eye trackers. Blinks and extreme downgaze result in transient loss of tracking in both eyes. If the eyes become highly converged, corneal reflections can migrate onto the temporal conjunctiva and pupil tracking can be impaired. Niehorster and colleagues[24] created open-source software for an earlier model, Tobii Pro Glasses 2, which detects data gaps and fills them with missing samples. We applied two filters to the data obtained from the Tobii Pro Glasses 3. The first filter filled in gaps lasting up to 25 samples with the median of the surrounding 24 samples. This eliminated blinks and other brief artifacts. Although a half second fill-in is long in the context of saccade duration, it is a reasonable compromise when monitoring vergence shifts, which occur on a slower time scale. The second filter removed spurious readings by comparing the value of each point with the 24 points surrounding it. If more than 1° outside the median, it was replaced with the median value.

The JSON file also provides a 3-dimensional gaze origin variable for each eye, measured at 50 Hz. The horizontal component, denoted x, represents the distance of the pupil center from the cyclopean axis, where the scene camera center is located. Interpupillary distance was derived by adding the absolute values of the horizontal gaze origin component for the right eye and the left eye. The distribution of interpupillary distances, which changes with vergence angle, was determined over the duration of each recording.

Experimental Subjects

This study was approved by the University of California, San Francisco (UCSF) Institutional Review Board and followed the principles of the Declaration of Helsinki. Informed consent was obtained from adult subjects. Minors provided their assent and a parent gave informed consent.

In the first part of this study, the functional capability and reliability of the Tobii Pro Glasses 3 instrument to measure vergence angle was defined in laboratory experiments conducted in 4 adult subjects, 2 of them authors of this paper. In the second part, 10 healthy subjects ranging in age from 10 to 67 years wore the eye tracking glasses for a prolonged period while going about their daily activities. All subjects had normal visual function, verified by ophthalmological examination, including assessment of acuity, pupils, eye movements, stereopsis, and fundi. Subjects with pathological nystagmus, strabismus, corneal disease, or prior ocular surgery were ineligible. No refractive correction was necessary for the subjects who participated in the testing of the performance of the Tobii Pro Glasses 3 in the laboratory, but some subjects engaged in ambulatory monitoring wore soft contact lenses or spherical corrective lenses that fit into the glasses' frames. Two ambulatory subjects were presbyopic. They were tested without near correction, which may have affected the percentage of time they spent engaged in near tasks. In principle, bifocal lenses could be fabricated for use with the eye tracking glasses.

For the laboratory testing, each subject sat in a chair with the head immobile in an adjustable chin/forehead rest mounted on a table that could be moved vertically. The room was lit with fluorescent lights at a typical indoor brightness level (500 lux). The tracker was found to perform erratically in dim light, presumably because the dilated pupil is clipped by the upper eyelid. It also performed unreliably in direct sunlight, unless the infrared-blocking lenses were worn, because the corneal reflections from the illuminators were washed out by solar light.

Each subject fixated a crosshair target mounted on a tripod at eye level, placed at the appropriate distance for a series of vergence demands: 0.25, 0.5, 1, 2, 4, 8, 16, and 32°. Subjects' interpupillary distances were measured manually using a ruler (60, 64, 65, and 68 mm) and also reported by the eye tracking glasses (60.5, 64.5, 64.1, and 67.7 mm) during distance fixation. The value provided by the glasses was used to calculate the viewing distances for each subject's series of vergence angles:

$$Viewing\ distance = \frac{\frac{1}{2} \times interpupillary\ distance}{tan\ \left(\frac{1}{2} \times vergence\ angle\right)}$$

Specific information about each experiment is provided as the data are described in the Results.

For the ambulatory recordings of vergence angle, 10 subjects were asked to wear the eye tracking glasses for as long as they were willing, while engaged in their normal routine over the course of a day. Some subjects reported discomfort from the hard plastic nosepiece, due to the weight of the eye tracking glasses (60.0 g), sunglasses (30.7 g), and corrective lenses (17.3 g). The right temporal piece of the glasses became hot during prolonged recordings, bothering some subjects. Otherwise, the glasses did not interfere with routine activities, such as driving, running, shooting baskets, watching television, working at a computer, etc. Subjects were instructed to remove the eye tracking glasses before entering a lavatory. When placed back on the head, they immediately resumed tracking with the same calibration.

An Igor Procedure File and the subjects' data are available at Open Science Framework via this link: https://osf.io/fesdp/?view_only=864465d515c649938f82d466731db2ef.

Results

Laboratory Testing of the Tobii Pro Glasses 3

The first experiment was designed to test if the Tobii Pro Glasses 3 accurately reported a vergence angle of 0° when a subject looked at infinity. Our longest indoor room was only 16 m long. As a compromise, we had the subject fixate a target at 14.68 m, corresponding to a vergence demand of 0.25°. Figure 2A shows a recording obtained while the subject fixated continuously for 15 minutes. There was a slow conjugate 4° rightward drift in eye position. This was unexpected, because the subjects in these experiments fixated the crosshair so faithfully that visual fading occurred for objects located in their peripheral visual fields. The most likely explanation is that the subject's head turned slightly leftward during the recording (no strap was used to prevent head rotation). The mean vergence angle reported by the instrument was 3.0 ± 0.5°, representing an error of 2.75° (Fig. 2B). This discrepancy means that although the subject was fixating at 14.68 m, the instrument recorded that he was fixating at 1.22 m.

In Figure 2C, the recording is split into individual 1-minute epochs, revealing a family of histograms, each narrower than the overall 15-minute envelope. The peaks range between 2.4° and 3.4°. This finding reveals that the vergence angle recorded by the device during constant distance fixation drifts on a time scale of minutes over about a degree.

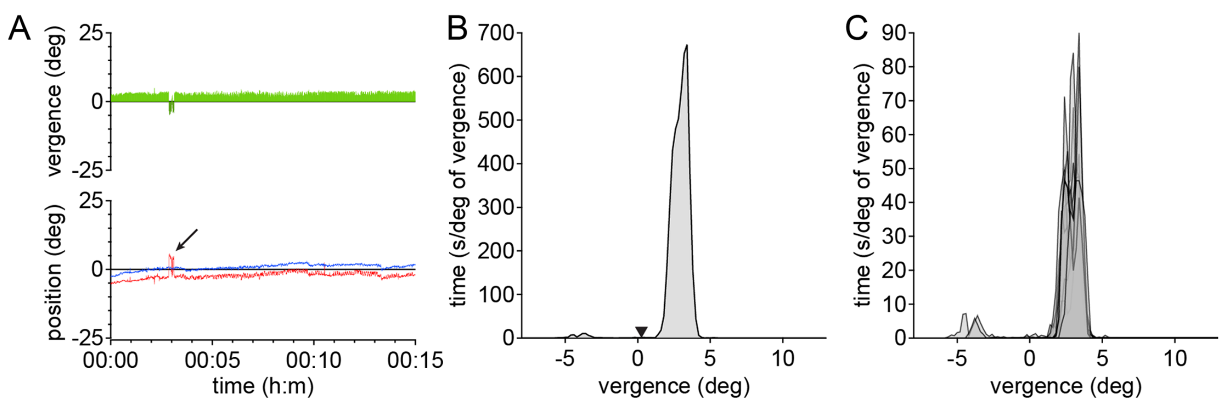

Figure 2. Vergence angle during steady fixation on a crosshair target at 14.68 m for 15 minutes after calibration at a distance of 75 cm. (**A**) Eye positions (positive values denote right gaze) show a mostly parallel drift of about 4° in the position of each eye (red = right eye and blue = left eye). Coughing at 3 minutes (*arrow*) produced an artifact in the right eye trace, giving a transient negative vergence value. (**B**) Histogram of vergence angle in **A**, plotted in 0.2° bins (positive values denote convergence). The vergence demand calculated from the subject's interpupillary distance of 64.1 mm was 0.25° (*arrowhead*), but the mean value measured by the instrument was 3.0 ± 0.5° (range = 1.3–4.6°). (**C**) Same vergence data plotted in 15 sequential 60-second intervals show fluctuations minute-by-minute in the measurement of vergence angle, with individual peaks ranging between 2.4 and 3.4°. Spurious readings at −5° were from coughing.

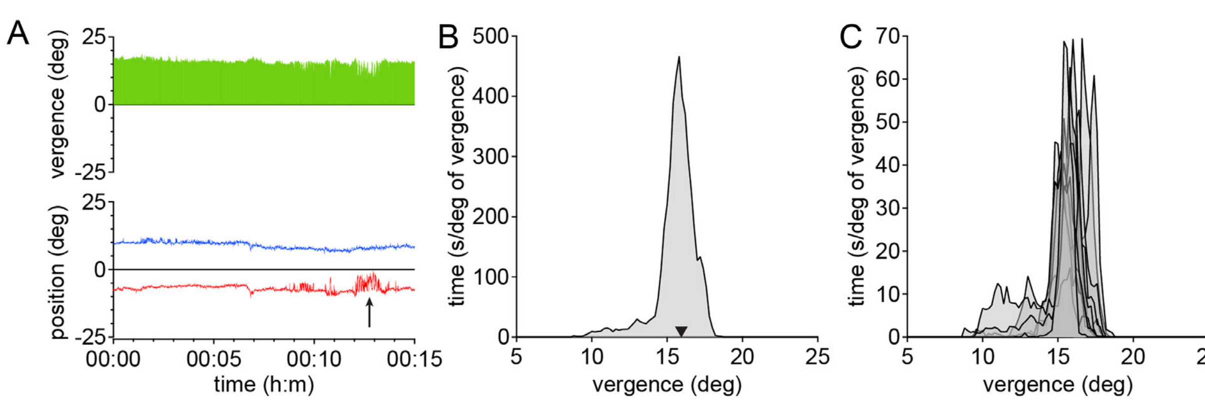

Figure 3. Vergence angle during steady fixation by the same subject in Figure 2, viewing a crosshair at 22.8 cm for 15 minutes, requiring vergence of 16°. (**A**) Position traces showed a slight outward drift of the eyes over this interval, although the subject reported a single, fused fixation target throughout the recording. Artifact appeared in the right eye trace (*arrow*), without known cause. (**B**) Vergence angle in **A** was 15.7 ± 1.3°. (**C**) Fifteen sequential 1 minute plots of data, showing variability in measurements of vergence angle over time.

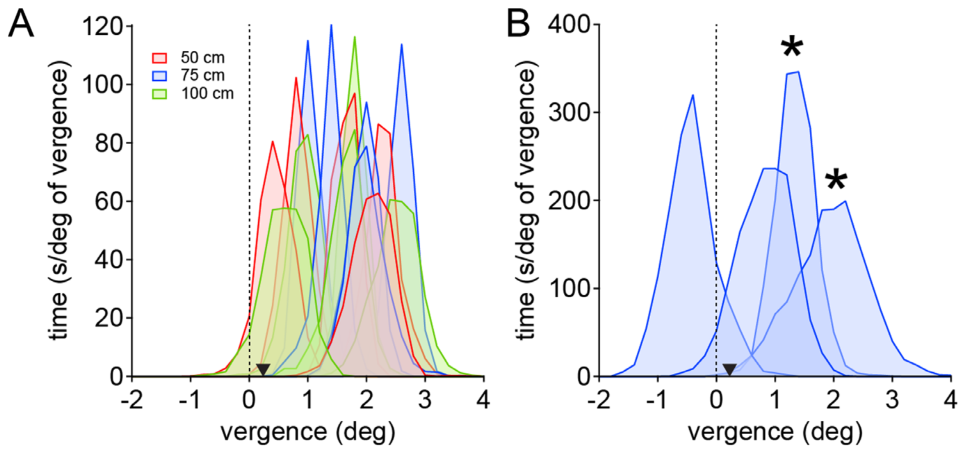

Figure 4. Calibration distance does not affect measurement of vergence angle by the eye tracking glasses. (**A**) Histograms of vergence angle, recorded 5 times, for a 1-minute duration, for each calibration distance. Each recording was done after a fresh calibration performed by fixation on a bull's eye target at 50, 75, or 100 cm. The subject, with an interpupillary distance of 60.5 mm fixated at 13.87 m, corresponding to a vergence demand of 0.25° (*arrowhead*). Scatter in measurements is unrelated to the calibration distance used. The mean vergence was 1.7 ± 0.7°, an error of 1.45°. (**B**) Histograms of 4 epochs, each lasting 5 minutes, from a different subject fixating at 15.52 m for a vergence demand of 0.25° (*arrowhead*). Calibration was obtained at 75 cm; two peaks marked with an asterisk were performed with the same calibration. The mean values ranged from −0.32 to 2.05°.

Next, the experiment was repeated in the same subject, now converged on the crosshair at 16° (Fig. 3). The goal was to compare the tracker's accuracy at a low versus high vergence angle. The right eye's trace was more irregular than the left eye's trace, with a 2 second interval marred by unexplained artifact. The mean vergence measurement was 15.7 ± 1.3°, a more accurate reading than recorded while fixating near infinity (compare Fig. 2B to 3B). Individual 1-minute epochs showed jitter in the position of the peaks, as observed at 0.25° (see Fig. 3C).

Given this apparent difference in the accuracy of vergence angle measurements while fixating at near versus far, we sought to determine if the distance at which calibration is performed is an important factor. The manufacturer recommends viewing the bull's eye target at a distance between 50 and 100 cm for calibration of the eye tracking glasses. Our testing showed that calibration fails outside a range of 40 to 120 cm. Figure 4A shows data from a subject in whom calibration was obtained 5 times in random order at 50, 75, and 100 cm. Subsequent fixation at distance (0.25° vergence demand) after each calibration showed scatter in the 15 individual 1-minute measurements of vergence angle. The scatter was unrelated to the calibration distance used to make the recording.

Figure 4B shows data from a different subject, also fixating on the crosshair target at a distance requiring 0.25° of vergence. The subject fixated for 5-minute epochs after calibration performed at 75 cm. Individual peaks show scatter similar to that observed when calibration distance was varied (compare Figs. 4A to 4B). For two epochs, marked by asterisks, the same calibration was used. There was still nearly a 1° offset in the peaks. From these experiments we concluded that tracker accuracy is not affected by the choice of calibration distance between the range of 50 and 100 cm. For the sake of consistency, we decided to perform all subsequent calibrations at 75 cm.

Figure 5 shows data from the 4 subjects fixating the crosshair for 5 minutes at distances that correspond to a series of increasing vergence demand: 0.25–32°. The traces of eye position contain noise, especially at 32° (see Fig. 5A). The location and width of peaks is variable among subjects and at different vergence angles (see Fig. 5B).

Figure 6 illustrates the errors in accuracy and precision that occurred among subjects in the measurements provided by the eye tracking glasses at different vergence demand. At distance, the eye tracking glasses usually reported values greater than the actual vergence demand. At 32°, they reported a mean value of 28.9°, which was less than vergence demand. Subjects denied diplopia at 32°, even though required to sustain a highly convergent angle for 5 minutes, so the discrepancy was likely due to tracker inaccuracy rather than inability to maintain a highly converged posture.

An important issue for prolonged ambulatory recordings is whether the eye tracking glasses can provide accurate, stable readings over a period of many hours. To address this issue, a subject wore them for 2 hours. Every 15 minutes, he fixated the crosshair at

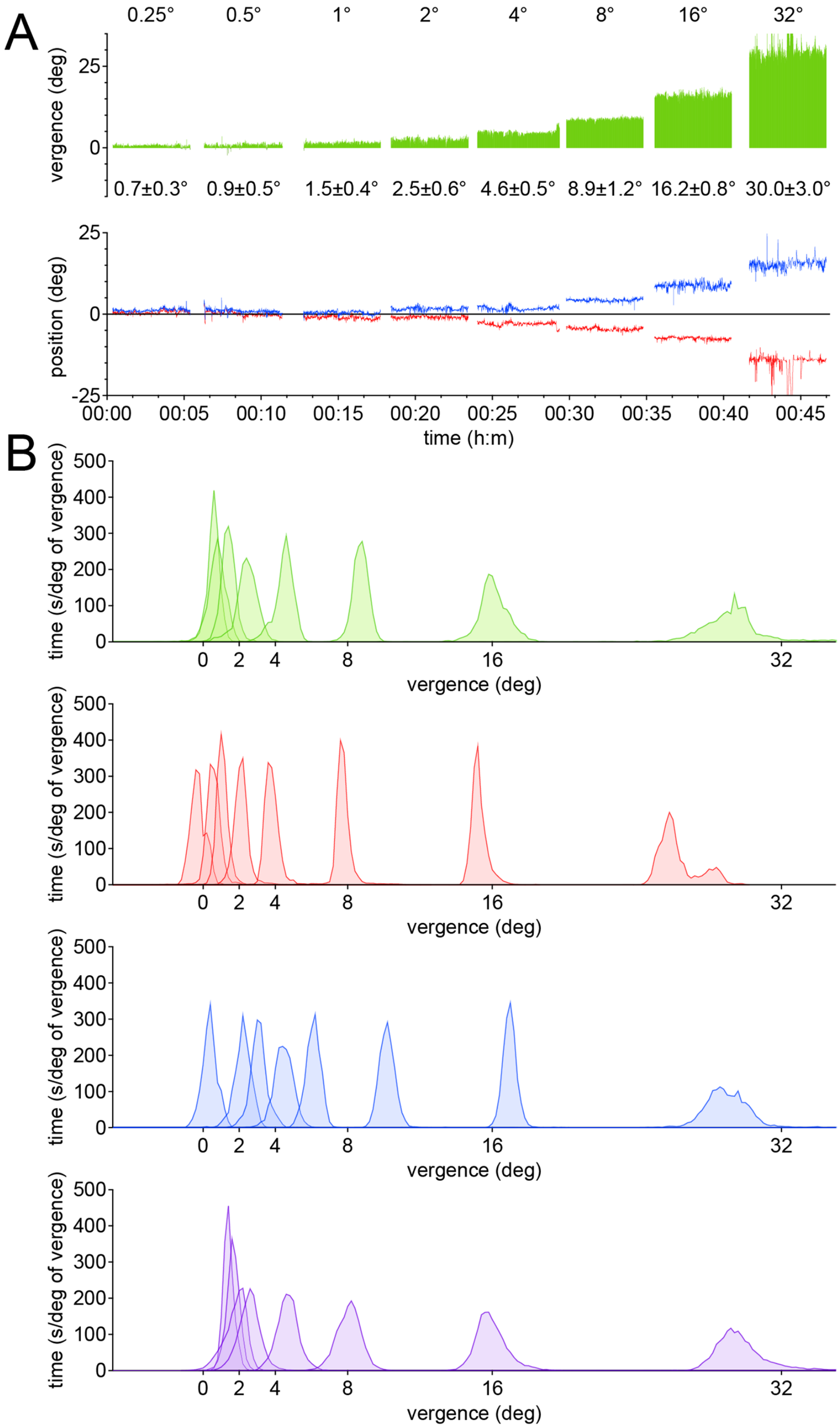

Figure 5. Variation in vergence angle measurements among subjects. (**A**) Eye position traces from a subject fixating at decreasing distances corresponding to vergence demands of 0.25, 0.5, 1, 2 4 8, 16, and 32° (*top row*). Each epoch lasted 5 minutes; gaps in the traces are from brief intervals between each fixation period. Tracker noise was most evident at 32° vergence angle. Mean vergence is listed below each plot. (**B**) Data from 4 subjects (top series from subject in **A**), fixating for 5 minutes at each distance corresponding to the 8 vergence angles. Measurements deviate from the true vergence angle for some trials, and this error varies from subject to subject.

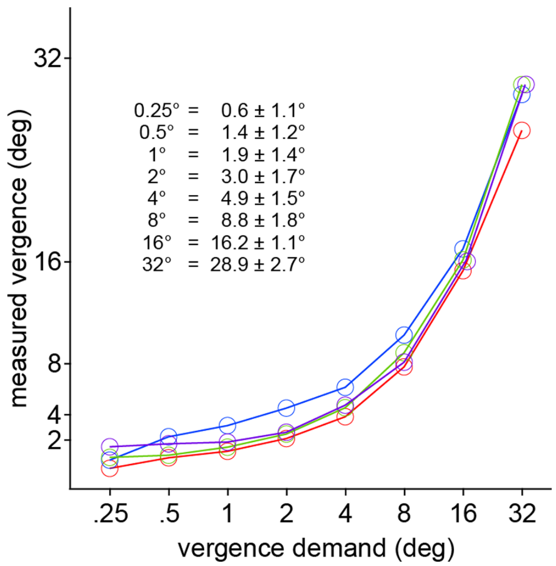

Figure 6. Plot of vergence demand versus measurement rendered by the eye tracking glasses. Data from Figure 5, showing mean of the measured vergence at a range of vergence demands (0.25–32°) in each subject. Inset table shows (left) vergence demand and (right) measured mean vergence.

distance at a vergence angle of 0.25° for a period of 60 seconds (Fig. 7). Between these epochs of crosshair fixation his behavior was unconstrained – but he spent most of his time working at his computer. The mean vergence angle measured during the 9 distance fixation epochs was $2.0 \pm 0.3°$ (see Fig. 7B). Although there was an offset of 1.75° from the vergence demand, the data from each 60-second epoch showed no systematic drift over time (see Fig. 7C).

Figure 8 explores the impact of the median filters on the raw data traces. It shows a 5 second data excerpt from the subject shown in Figure 7, who was fixating at a vergence angle of 0.25°. Gaps and noise are present in the instrument's position signals, even though the recording was made under optimal, head-stabilized conditions. As a result, the eye tracking glasses sometimes falsely reported a divergent (exotropic) alignment during fixation at distance. Gaps $\leq$0.5 seconds, which occurred frequently in the position signal from one or both eyes, were filled in by the first median filter. This had the benefit of increasing the total duration of the recording. The second median filter was applied to mitigate inaccurate position signals, which often surrounded gaps in the recording traces. Application of this filter was intended the remove erroneous vergence angle readings, but sometimes it exacerbated recording artifacts (compare Fig. 8A to 8B). This was especially true when unequal gaps occurred in the record of each eye, in conjunction with an abrupt change recorded in the position of only one eye.

Long Term Recording of Vergence Profiles in Ambulatory Subjects

Figure 9 shows data from a subject recorded in the second portion of this study, under free ranging conditions. Immediately following tracker calibration at 75 cm, the subject fixated for 1 minute at a series of distances that corresponded to vergence demands of 0.25 to 32°. The distances were measured with a retractable steel tape measure and the fixation target

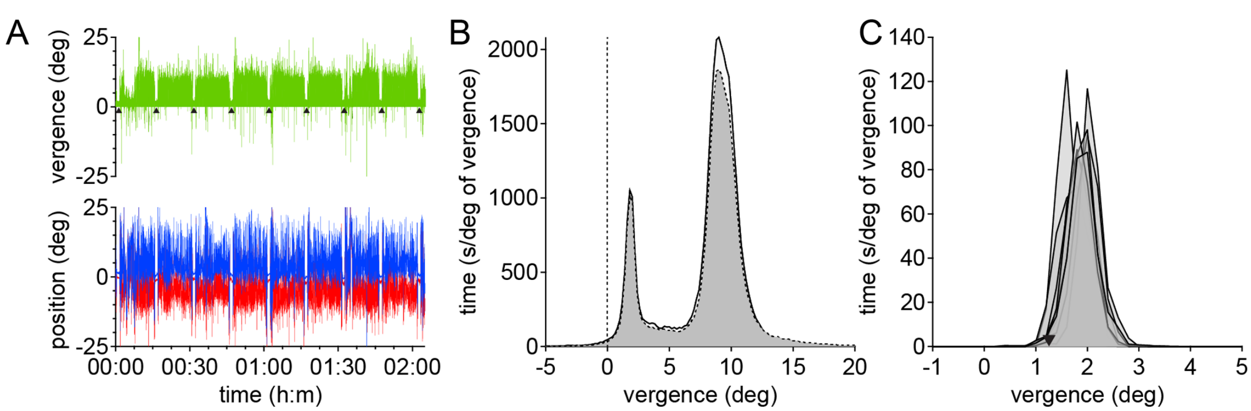

Figure 7. Stability of vergence angle measurement over time. (**A**) The tracking glasses were worn by a subject (same individual illustrated in Fig. 4A) for 2 hours, while working at a computer. Every 15 minutes (*arrowheads*), he was summoned to fixate for 60 seconds on a target at 13.87 m, a vergence demand of 0.25°. Note occasional negative spikes in vergence angle, due to artifact (Fig. 8). (**B**) Histogram showing vergence angle over 2 hours. The bimodal distribution reflects epochs working at near on the computer and fixating at distance on a target with the head stabilized. *Dashed line* shows unfiltered data; *solid line* shows data after application of median filters. (**C**) Plot of 9 histograms, each containing 60 seconds of data while converged at 0.25°, showing the consistency of readings compiled over 2 hours. The mean vergence measured $2.0 \pm 0.3°$, corresponding to an error of 1.75°.

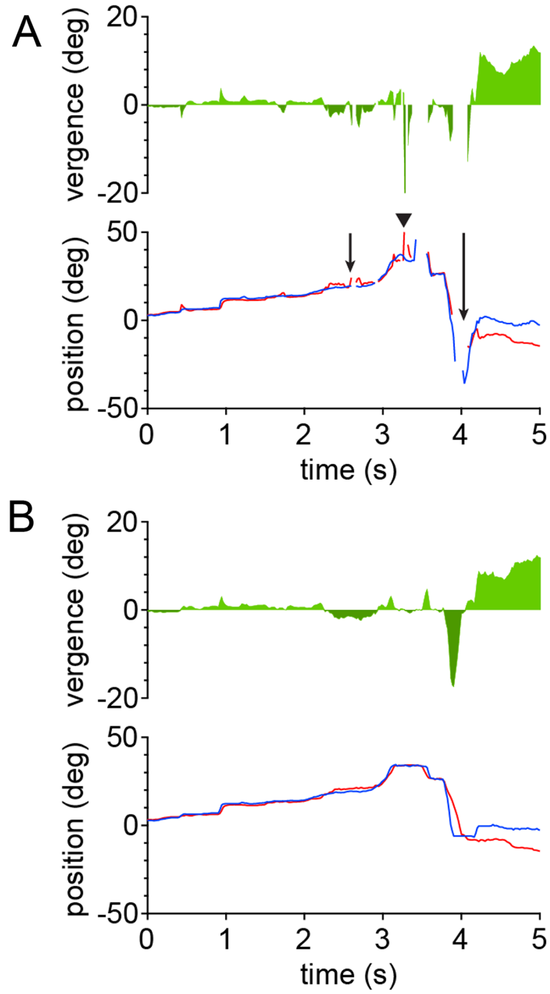

Figure 8. Effects of the data filters. (**A**) Five seconds of data from Figure 7A starting at 1:33:05 showing impact of applying the median filters. At 2.3 seconds, inaccurate right eye position signals from the eye tracking glasses produce a spurious exotropia (*short arrow*). At 3.3 seconds, inaccurate right eye position signals recur (*arrowhead*), causing another false exotropia reading, a transient deflection to −20°. Later, several breaks occur in both traces (*long arrow*), producing gaps in the vergence angle reading. (**B**) After application of the median filters, the data traces become continuous and the spurious exotropia spike of −20° is eliminated. Filling in subsequent gaps in the traces, however, exacerbates a large, artifactual exotropia deflection. This occurs because the slope of the right eye's trace, relative to that of the left eye, is altered by application of the median filters.

was handheld. The purpose of this procedure was to obtain recordings at known, fixed vergence demands to correct any errors in the vergence angle reported by the eye tracking glasses. Under these field conditions, measurements (see Fig. 9A) were less accurate and more variable than those obtained in the laboratory (see Fig. 5A).

Over a total recording time of 4 hours and 14 minutes, the subject engaged in various activities, reflected by the profile of her vergence behavior (see Fig. 9B). The unfiltered data had a duration of 2:16:29, which increased to 3:29:55 after application of the median filters. The filtered data were shorter than the total recording time because the subject took rest breaks and there were interruptions in the eye position signals that lasted more than 25 samples. Application of the filters "rescued" a greater percentage of the recording time during field recordings than during laboratory recordings (see Fig. 7B). This difference reflected the fact that cleaner data were obtained in the laboratory, so application of the filters had less impact. The filters greatly increased the duration of usable field recordings, without changing the overall shape or location of peaks in any subject's vergence profile.

Correlation with the video from the scene camera revealed that some of the distinct peaks were generated mostly by a single activity, such as viewing a smartphone or a computer monitor. Other activities, such as walking a dog or viewing a television, occurred at small vergence angles. They did not correspond uniquely to a single peak, because a mixture of many different behaviors shared the same small vergence angle. Another factor is that vergence angle changes less than 2° between infinity and 2 m. Given the limits of the tracker's accuracy, various activities conducted at slightly different distances within this range became merged in the subject's vergence profile.

In principle, negative vergence values present in the subject's vergence profile (see Fig. 9B) correspond to exotropic alignment of the eyes. The left shoulder of the subject's filtered data distribution strayed 10° into negative territory, representing 14.6% of the data in her vergence profile. Clinical examination revealed that this subject was orthotropic at distance. Therefore, all the negative points graphed in this subject represented inaccurate measurements of her vergence angle. Artifactual negative values were observed in subjects while they fixated both at distance (see Fig. 8) and at near (see Fig. 7A).

Figure 10 shows vergence angle profiles compiled from the other 9 subjects during prolonged ambulatory recordings. All the subjects were orthotropic at distance fixation. Therefore, as in Figure 9, all negative vergence values were a product of instrument noise. Subjects varied in the proportion of their data representing false exotropia readings; the subject in Figure 9 showed the largest error.

The individual vergence angle profiles varied considerably, because each person was engaged in different pursuits during their recording session. In general, there was a tendency for subjects' vergence behavior to exhibit two modes. Most subjects fixated

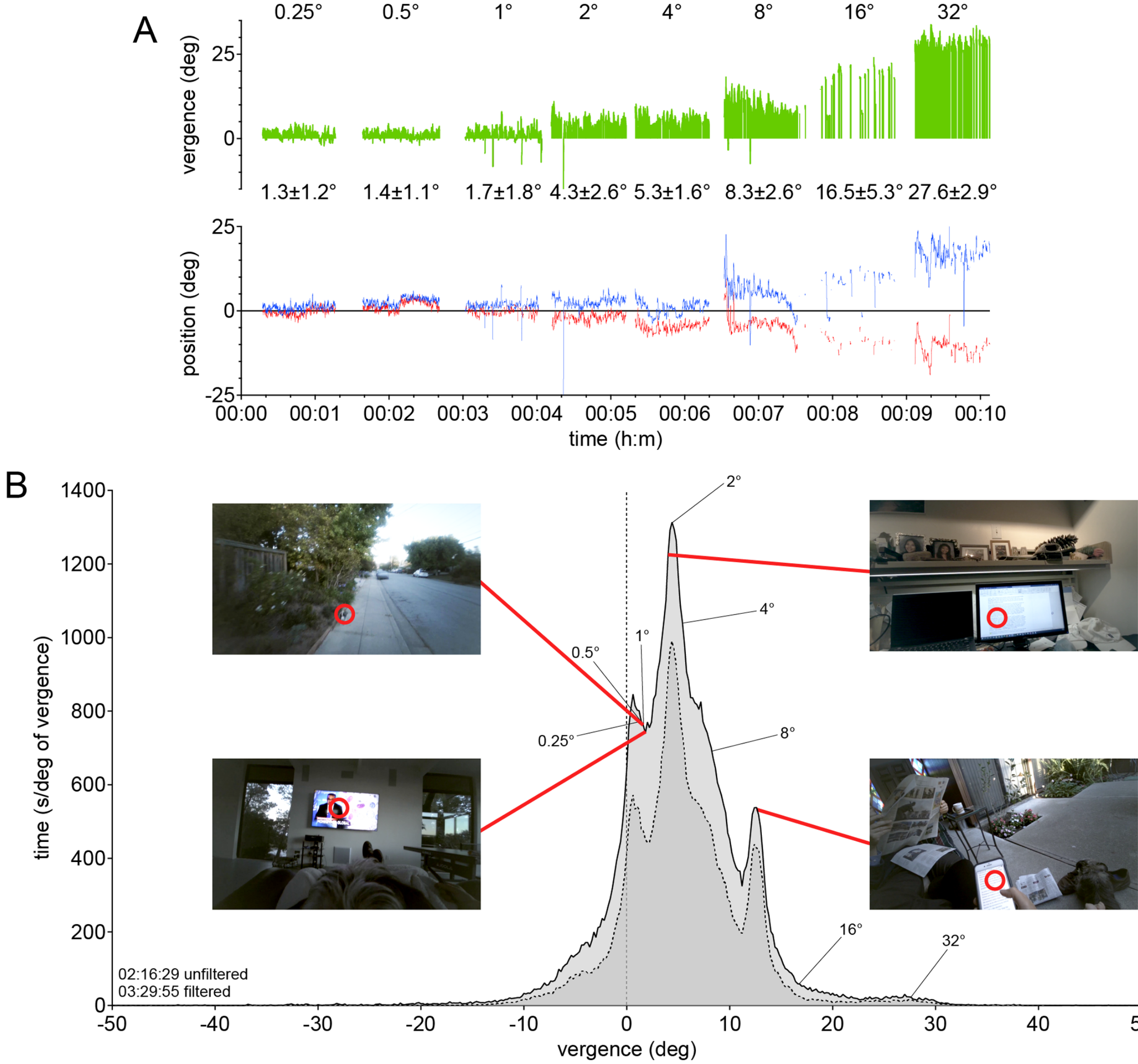

Figure 9. Vergence angle profile of a 52-year-old ambulatory subject. (**A**) Before the recording, her interpupillary distance was measured manually and then distances were calculated for target presentation at vergence angles ranging from 0.25 to 32°. The traces show more gaps, drift, and spurious points than data gathered in the lab (compare with Fig. 5A). Numbers in the *top row* denote vergence demand; and the numbers underneath indicate measured mean vergence. (**B**) Histogram showing the amount of time spent at each vergence angle. Dark shading represents unfiltered data. Mean value of data measured at each vergence demand in **A** is shown by *thin black lines*. *Red lines* point to mean value of vergence angle during the activity shown in the scene camera frame.

predominately at near or at far, generating a bimodal distribution of the data, with a relative paucity of intermediate points.

Shifts in vergence angle change the distance between subjects' pupil centers. Figure 11 shows plots of the 9 subjects' interpupillary distances measured during their ambulatory recording sessions. In each subject, the interpupillary distance ranged over about 4 mm. In most subjects, the plot of interpupillary distance closely followed the profile of vergence. This correlation was expected because information about the location of the pupil center, in addition to the illuminator reflections, is used by the glasses to track the eyes.

Figure 12 illustrates the relationship between vergence angle and interpupillary distance for a single subject (see Figs. 10A, 11A), sampled at 50 Hz over the course of more than 9 hours. There was a negative correlation ($r = -0.82$), with each 1 mm decrement in interpupillary distance corresponding to a 5.1° increase in vergence angle. For the 9 subjects, $r = -0.78 \pm 0.06$ and the mean increase in vergence angle was $4.9 \pm 1.4°$ per 1 mm decrease in interpupillary distance.

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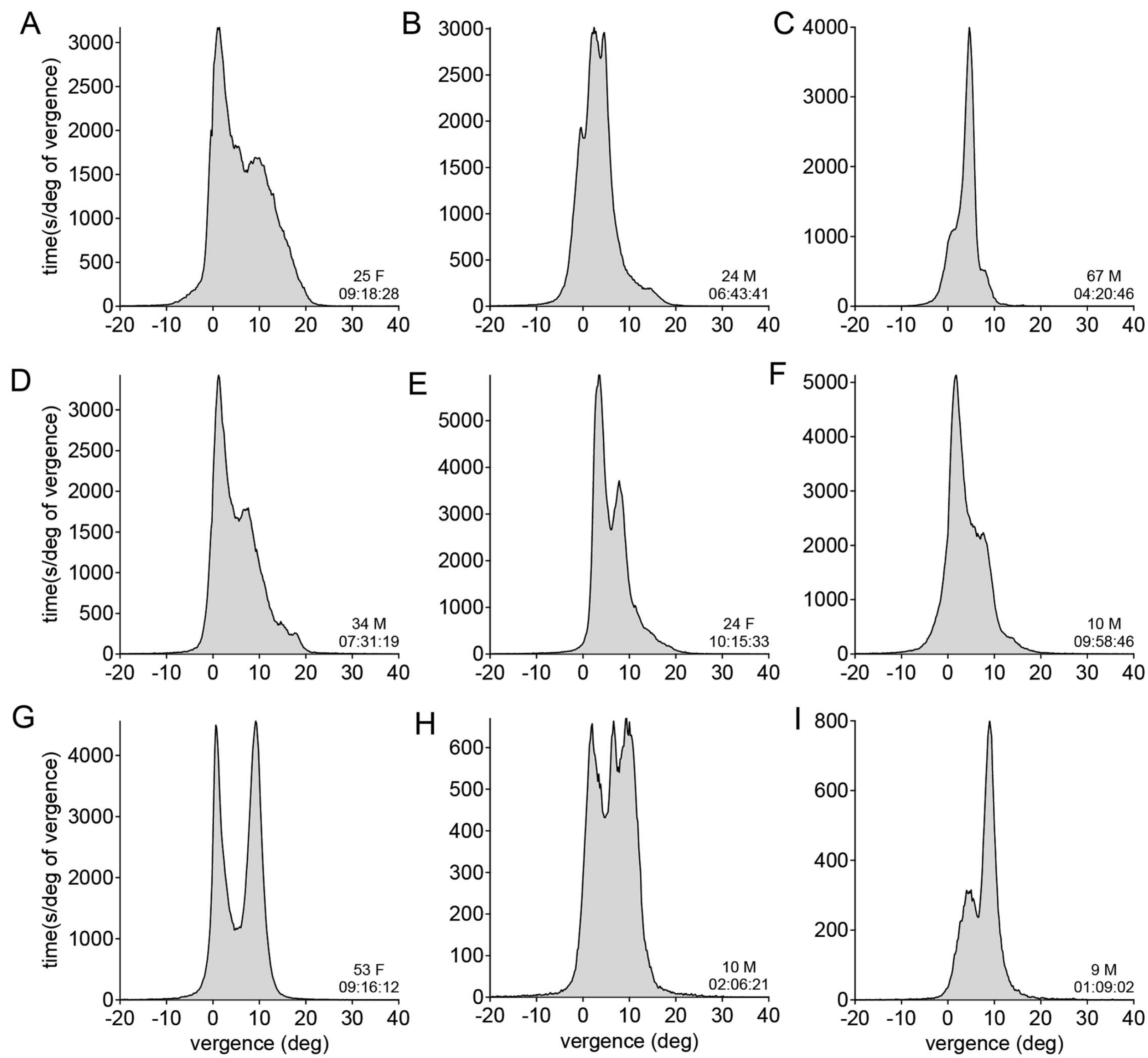

Figure 10. Variability of vergence angle profiles. (**A–I**) Vergence angle histograms from nine different subjects. Age, gender, and duration of filtered data are listed. Each profile is unique to the repertoire of activities in which the subject was engaged during the recording.

Discussion

The advent of eye trackers that can be worn by ambulatory subjects while engaged in their normal activities has opened a new field of investigation into human behavior. They permit one to compile data about eye movements and fixations made by individuals as they explore their environment over long periods in unconstrained settings. In this report, we show data from 10 normal individuals, capturing a history of the angle at which their eyes were converged (see Figs. 9, 10). Each profile was different, idiosyncratic to the tasks and actions of the subject, but several features were consistent. A large fraction of time was spent fixating at near targets, such as a mobile phone or computer monitor (or even a book). Much of the remaining time, fixation occurred between infinity and several meters. Fixation was relatively less frequent in the intermediate range, from just beyond the outstretched hand to several meters away. As a result, for many individuals, the profile of fixation distances had a bimodal distribution.

Ambulatory eye trackers have been useful for evaluation of performance in work settings. For example, they have been used to monitor the gaze of nurses in an intensive care unit, chefs cooking food, and workers in industrial occupations.[25–27] They may also prove valuable for early detection of impaired eye movements associated with certain movement disorders, such as

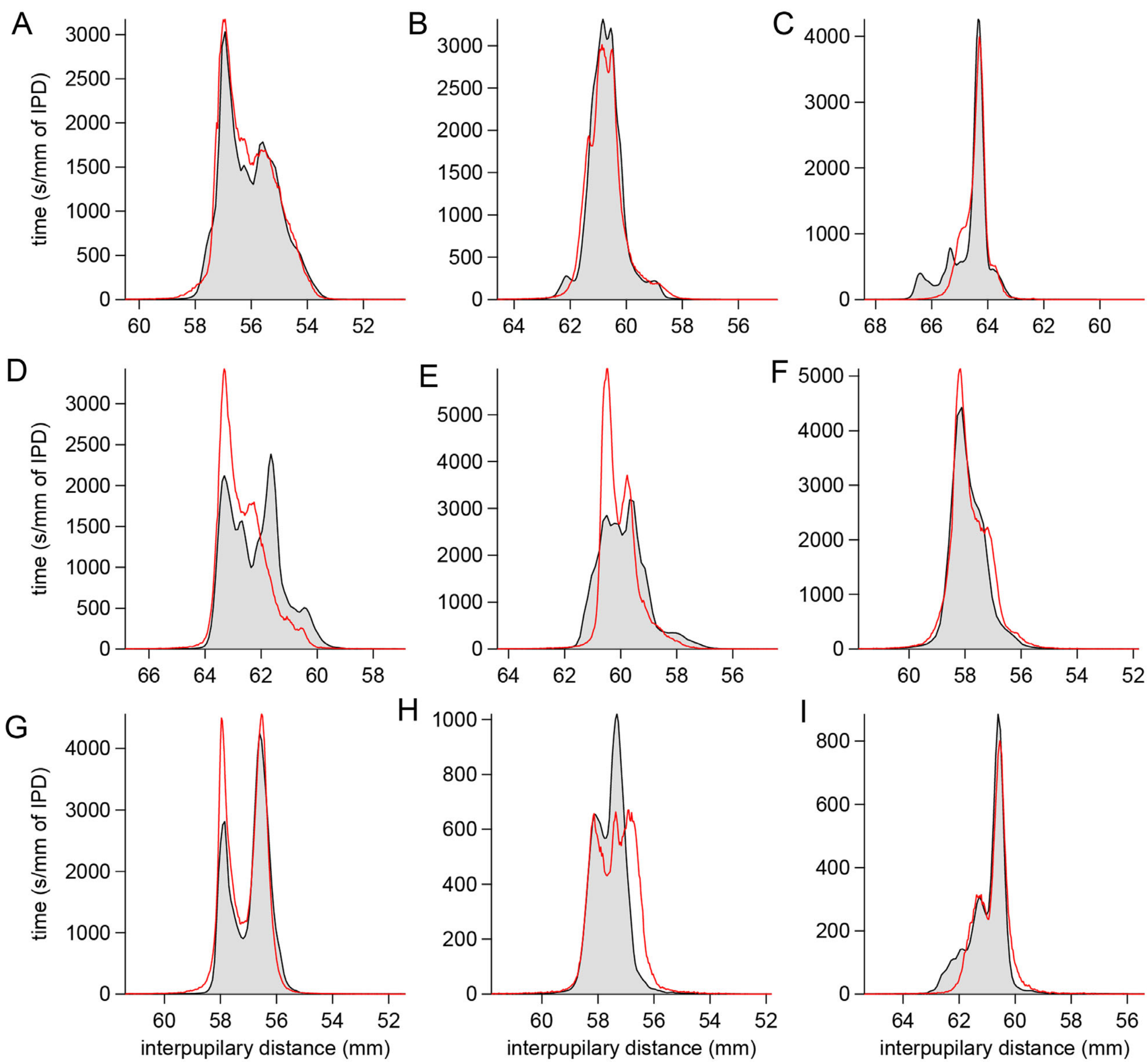

Figure 11. Interpupillary distance histograms for nine ambulatory subjects. (**A–I**) Same subjects shown in Figure 10, plotting the interpupillary distances at each moment during their recording session. Highest values correspond to the interpupillary distance in primary gaze, fixating at distance. Interpupillary distance ranged over 4 mm in most subjects and usually resembled the profile of vergence angle (*red outlines* from Fig. 10).

Parkinson's disease and supranuclear palsy. In Parkinson's disease, deficient convergence with diplopia at near is a prevalent symptom.[17,28,29] In patients with autism and schizophrenia, abnormal patterns of eye movement behavior have been identified.[30–35] It would be worthwhile to verify such observations, made in artificial laboratory settings, with recordings made in subjects' natural environments. Ambulatory recordings of eye movements may also serve to diagnose and monitor patients with ocular misalignment or strabismus, especially when findings are present only intermittently.[36]

It is important to evaluate the accuracy of face-mounted eye trackers to interpret the data obtained from ambulatory subjects.[23] Accuracy refers to the offset between the fixation position measured by the tracker and the subject's true fixation position.[37] Remote video eye trackers tested on stabilized subjects in the laboratory have an accuracy between 0.5 and 1°, measured in the X,Y plane.[38–44] Vergence angle is derived simply by subtracting the eyes' horizontal positions. Our measurements of the face-mounted Tobii Pro 3 eye tracking glasses, also tested under optimal conditions, yielded a comparable accuracy of

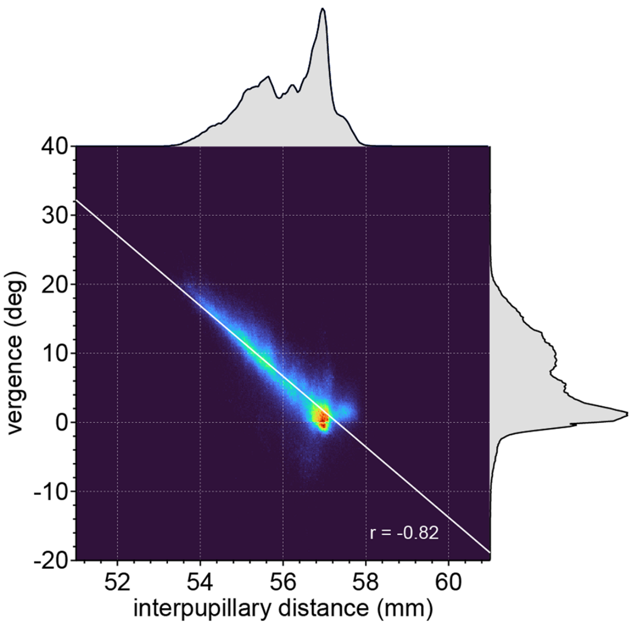

Figure 12. Correlation between vergence angle and interpupillary distance. Data from subject A in Figure 11, plotting interpupillary distance (approximately 1.7 × 10^6 samples) versus the simultaneously measured vergence angle. The Pearson correlation coefficient was −0.82. The histogram of the interpupillary distance is shown above; the histogram of the vergence angle is shown at right.

0.5 to 1° (see Fig. 6), except at the highest vergence angle (32°). Usually, the vergence angle reported was slightly too high during distance fixation and too low at the closest fixation point.

When deployed in ambulatory subjects, the Tobii Pro 3 eye tracking glasses were less accurate. Niehorster and colleagues[45] have noted the same trend when using remote eye trackers in unrestrained participants. In a typical subject (see Fig. 9A), the calibration traces showed an error of 4.4° at 32° convergence and an error up to 2.3° at other tested angles. The traces were also much noisier, with fluctuation and dropout of the eye position signal caused by tracker error. Our original intention was to use the measurements of vergence angle at known fixation distances made prior to each ambulatory recording to correct offsets in the value of vergence angle subsequently reported by the tracker. However, this proved of limited value, for several reasons. First, the error between vergence demand and recorded vergence varied at each distance, so a nonlinear data transformation would have been necessary. Second, it was difficult to measure fixation distances in the field recordings with sufficient precision.

In addition to accuracy, the variability (precision) of tracker output during steady fixation is an important index of instrument performance. In the laboratory, vergence demands of 0.25, 0.50, 1, 2, 4, 8, and 16° yielded values having a mean standard deviation ranging between 1.1 and 2.7° (see Fig. 6), with an absolute variation in eye position between 2 and 4°. For the ambulatory recordings, there was no way to assess variability in tracker recording of vergence, because vergence angle was not controlled. One gains some sense of the device's performance by observing the spread of reported vergence angles into the negative, non-physiological range. All negative values of vergence angle, signifying divergence of the ocular axis, were artifactual. Rather than displaying a sharp vertical cut off at 0° vergence angle, each subject's trace showed a tapered spread of errant negative values (see Fig. 10). Such false points were generated during epochs of near fixation and distant fixation (see Fig. 7). The variability of tracker measurements widened the spread of data points, but there is no indication that it caused a shift in the position of the peaks in any subject's profile.

The close inverse correlation (r = −0.78) between interpupillary distance and vergence angle (see Fig. 11) arises because the pupil centers are anterior to the centers of rotation of the globes. With each 1 mm decrease in interpupillary distance there was an increase in vergence angle of 5°. If one's goal in recording subjects is simply to track vergence angle, rather than the X,Y gaze position, it may be possible to use a device that relies only on detection of the pupil and measurement of its center position.[46] The additional information provided by the corneal reflection of the illuminators allows better registration of the eyes' fixation positions with the view provided by the scene camera. However, the complexity of the Tobii Pro Glasses 3 results in high cost, making them too expensive for many clinicians, who might consider using them to measure, for example, the magnitude and frequency of exotropia. Our data show that a simpler device that relies only on the location of the pupil centers might suffice for many applications.

Acknowledgments

Jessica Wong assisted with computer programming.

Supported by grants EY029703 (J.C.H.) and EY02162 (Vision Core Grant) from the National Eye Institute and by an unrestricted grant from Research to Prevent Blindness.

Ethics Approval: This study was approved by the UCSF Institutional Review Board and followed the principles of the Declaration of Helsinki.

Consent to Participate: Informed consent was obtained from adult subjects. Minors provided their assent and a parent gave informed consent. Consent included permission to publish data findings.

Availability of Data, Materials, and Code: All eye movement data obtained from the 14 subjects are available at Open Science Framework via this link: https://osf.io/fesdp/?view_only=864465d515c649938f82d466731db2ef.

Authors' Contributions: M.D.D., T.N.G., J.R.E., and J.C.H. contributed to carrying out the experiments, interpreting the data, and preparation of the manuscript.

Disclosure: **M.D. Dilbeck**, None; **T.N. Gentry**, None; **J.R. Economides**, None; **J.C. Horton**, None

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