1040-5488/15/9211-1103/0 VOL. 92, NO. 11, PP. 1103–1112
OPTOMETRY AND VISION SCIENCE
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ORIGINAL ARTICLE

OPEN

Head-Eye Coordination Increases with Age and Varies across Countries

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ABSTRACT

Purpose. Head movements in older people may contribute to their dizziness and equilibrium problems. Head gain is the ratio of head movement to total movement (head + eye) when executing a saccade to an eccentric target. Two studies have investigated the relationship between head gain and age but have provided conflicting results.

Methods. We report head gain data collected from research laboratories and optician stores. Our sample sizes are much larger (n = 657 for laboratory, n = 64,458 for optician stores), permitting more detailed analyses.

Results. The head-eye coefficient, expressed as 100 times the square root of head gain, was bimodal with one mode of primarily eye movers and one mode of eye-and-head movers. Head-eye coefficient increased with age and was invariant with eye correction and gender. We also found an effect of nation that seemed associated with gross domestic product or by latitude (in the northern hemisphere) and log population density.

Discussion. Assuming that head movements and visual distortions contribute to dizziness and equilibrium problems, our study suggests that customizing eyewear based on age and country may help in reducing the prevalence of problems associated with head and/or eye movements.
(Optom Vis Sci 2015;92:1103–1112)

Key Words: head-eye coordination, saccades, age, ethnicity, eye correction

Saccades made toward eccentric targets (>10 to 15 degrees of eccentricity) are often accompanied by head movements by unrestrained participants. There is considerable individual variability in the amount of head rotation[1–3] that remains unexplained by neck or ocular motor range[4] or the high ocular accuracy range.[5]

Effect of Age

Head gain is the ratio of head movement to total movement (head + eye) when executing a saccade to an eccentric target. Two studies have investigated the relationship between head gain and age, with conflicting results. The first study by Proudlock et al.[6] found that younger participants were primarily eye movers, whereas older participants included both primarily eye movers and eye-and-head movers. The second study by Thumser et al.[7] found no correlation of head gain with cognitive functioning measures, and at most a mild reduction of head gain with age. Younger participants included many that made considerable head movements. A possible cause for the discrepancy may be low sample sizes for a comparison between groups in the presence of high individual variability.

Effect of Glasses

Another issue is whether wearing glasses affects head movements. Again, past studies provide conflicting results. Larger-amplitude head movements have been described in a group of presbyopes when wearing progressive lenses compared with the same subjects wearing single vision lenses.[8] Proudlock et al.[6] also mentioned a link between wearing glasses and head movements, but that effect disappeared when controlled for various factors including age.

The issue is particularly relevant as head gains are affected by paralysis or field-of-view occlusion.[9–13] Stahl[14] found that restriction of neck movement reduced head gain even after the restriction was removed. Occlusion of field of view increased head gain but only during occlusion[11,14]; normal head gains returned after removal of occlusion.[14] If these results generalize to long-term usage of glasses, which are known to produce a degradation of peripheral vision quality, then head gains could be affected by correction strength.

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Cultural Effect

Cultural differences in gaze and saccade behavior are well documented.[15] For example, there are cultural differences in fixation patterns during face tasks,[16] in express saccades,[17] and in fixation patterns to visual novelty in scenes[18–20] (but see Ref. [21]). To our knowledge, no previous study investigated whether these biases might generalize to head-eye coordination.

The Importance to Balance

It has been suggested that the head position plays an important role in equilibrium.[22] Possible causes of dizziness and equilibrium problems encountered by older people include (1) reduced vestibular ocular reflexes,[23–25] (2) distortions of the visual field produced by glasses,[26] and (3) higher head gains.

Research Goals

The individual variability of eye-head coordination strategy has been used by Essilor for the conception of personalized progressive eyeglass lens[27]: the Varilux Ipseo. To provide this customized lens, the precise visual strategy of each person is measured by the VisionPrint System (VPS; full description below). Then, lenses are designed to reduce aberrations in accordance with the person's visual strategy. Since the launch of Varilux Ipseo in 2003, the VPS was used throughout the world in tens of thousands of optician stores. Furthermore, this tool has been extensively used and evaluated in the ESSILOR R&D facilities.

The primary goals of this study are (1) to resolve conflicts in past results,[6,7] (2) test additional factors that may affect eye-head coordination, and (3) provide an estimate of eye-head coordination for situations where VPS measurement is impractical. This database of 65,115 participants allows for high statistical power even for more detailed analyses.

The current study does not include measures of dizziness and equilibrium. Further studies on large samples could include questionnaires to evaluate the prevalence of dizziness and equilibrium problems. The VPS measures head movements in conditions where there are frequent saccades to eccentric targets. This replicates scenarios in which we expect dizziness to be more prevalent. Real-world scenarios requiring frequent saccades to eccentric targets include driving or crossing a street.[28] We note, however, that head movement strategies differ greatly in other scenarios,[29,30] for example, during manual work where people tend to produce fewer saccades to eccentric locations.

METHODS

Participants

Two different databases of VPS values have been extracted and analyzed in the current study. The "laboratory sample" (n = 657) came from ESSILOR R&D laboratories in Montréal (Canada), Paris (France), and Singapore (Asia). This database contains information about gender and age, except for 36 participants in the Asian group for whom gender was unknown. The "opticians" database (n = 64,458) came from optician stores in Europe, Asia, and the United States and does not contain information about gender or age. Most analyses were performed on the two data sets combined (henceforth referred to as the "full sample"). Testing in laboratory and optician stores used the same VPS system, which comes with a user's guide detailing the proper setup, calibration, and usage.

To avoid small sample sizes when comparing nations or ethnicities, where appropriate to our research questions, (1) we regrouped samples together across regions sharing an ethnicity and/or (2) we regrouped the Canadian and French laboratory groups into one "Caucasian laboratory" sample to contrast with the "Asian laboratory" sample.

The study complied fully with the Declaration of Helsinki, and written informed consent was obtained from all laboratory subjects involved in the study. Commercial data from optician stores were not obtained with informed consent. However, these data were nonnominal and did not include identifying information; thus, privacy was ensured. This study was approved by national ethical committees.

Apparatus

The VPS was used to display fixation points to which participants made saccades. This tool is composed of one central box and two removable arms (Fig. 1). Three light-emitting diodes (LEDs) are used to elicit eye-head movements: one toward the center of the box and two at the extremities of both arms. The participant is seated in front of the system, wearing a 120-Hz ultrasonic tracker mounted on goggles. Participants did not wear their glasses during the experiment to avoid peripheral distortion effects caused by glasses. Head-eye coordination was unaffected by target size in a saccade task similar to the one used here[31]; therefore, we expect our results to generalize across blurred or corrected vision.

The central control screen gave the participant's distance relative to the ideal distance (40 cm) such that participants could position themselves. This step serves both as calibration and diagnostics; no further calibration is necessary. Participants viewed the apparatus' LEDs at a downward angle of approximately 30 degrees.

Once the position was validated, peripheral LEDs had an eccentricity of ±40 degrees. The ultrasonic tracker used two sound

FIGURE 1.

The VPS used to measure individual head-eye coordination strategy. A color version of this figure is available online at www.optvissci.com.

sources placed on the glasses a few millimeters apart from each other and a receptor on the machine to register the phase difference, which is directly proportional to the horizontal rotation of the head. During our task, we did not measure eye movements. However, an internal unpublished study (Essilor R&D, Paris) using a similar protocol has verified on a smaller number of participants that eye saccades during the task were accurately made to the visual targets.

The testing sequence for measuring eye-head strategy was the following: a beep sounded and the central LED turned on simultaneously. The beep duration was 1 second, whereas the LED duration was 2 ± 0.5 seconds to avoid a learning effect. When the central LED turned off, one of the two peripheral LEDs turned on. The participant was asked to saccade to the corresponding peripheral LED. The peripheral LED turned off after 1 second, and another trial started with the central LED and beep. A complete session involved 25 sequences: 5 practice trials (alternating sides; excluded from the analysis), followed by 20 measurement trials (10 per side, in random order).

Analyses

Two standard definitions of head movements exist in the literature: (1) the total movement of the head from start to finish and (2) the amount of head movement contributing to the accomplishment of the gaze shift.[32] We used the former definition because it represents a larger proportion of time spent viewing targets than the latter definition; thus, the former definition is more closely related to normal viewing conditions.

Head gains were defined as the head amplitude, in degrees, from the "straight ahead" position (when looking at the center target) to the peripheral position, divided by the eccentricity of the target (40 degrees). Thus, a head rotation of 20 degrees equals a gain of 0.5. Head gains were averaged over the 20 measurements (10 left and 10 right) before further analyses.

Head gains were positively skewed. We transformed our data to "head-eye coefficient" (HEC) using equation 1:

$$\mathrm{HEC} = \begin{cases} 100, & \text{if}(\text{Head Gain} > 0) \\ 0, & \text{if}(\text{Head Gain} < 0) \\ 100\sqrt{\text{Head Gain}}, & \text{otherwise} \end{cases} \qquad (1)$$

Head-eye coefficient scores were distributed between a natural minimum of 0 (0% head movement, 100% eye movement) and a maximum of 100 (100% head movement, 0% eye movement). Head-eye coefficient reduced skew and produced clear bimodality that was more reliably fitted than other transformations. We considered other transformations (e.g., logarithmic,[6] logit); however, the quality of bimodal fits was markedly improved using the HEC transformation.

The ratio of eye-and-head movers to eye movers was calculated in two ways: (1) using bimodal fits or (2) using a HEC cutoff of 25. Bimodal fits were performed using the following steps: (1) two Gaussian distributions were fitted by eye to the distribution; (2) the means, SDs, and maxima of the Gaussians were adjusted using a search algorithm to minimize the least-squares fit between the maxima of the two Gaussians and the histograms; and (3) the solution was verified by eye and repeated if necessary. Both methods produced similar results. We report HEC cutoff results because it was the more reliable and less subjective method of the two methods mentioned.

Because of high sample sizes, even small effects were statistically significant; for example, for the laboratory sample, r values greater than or equal to 0.1 were associated with p values less than or equal to 0.0127. For this reason, we did not report r values less than 0.1. Correlations were corrected for family-wise error among 21 comparisons.

We did not correct t tests for family-wise error because (1) the correction level needed depends on the subjectively determined number of comparisons that are included in a given set of tests, and (2) in most cases here, different analyses are tied to different research questions, in which case family-wise correction does not apply. Instead, we emphasize results that remain significant even at conservative levels of correction and include effect sizes (Cohen d).

A separate set of analyses was performed on group data separated and averaged for each of 12 locations: United States, Japan, Belgium, France, Spain, Indonesia, Singapore, Thailand, South Korea, India, Montreal, and Hong Kong.

Sample Size

Thumser et al.[7] compared a total of 72 participants across two age groups, whereas Proudlock et al.[6] compared a total of 53 participants spread across three age groups. They found opposite results. Our sample size of participants with known age was much higher (n = 657), with our young and old age groups having 175 and 482 participants, respectively.

Parametric tests (e.g., t test, analysis of variance) assume that data are normally distributed. The population distribution of HEC is bimodal, and the two modes have different distribution widths. For these reasons, we conducted power and bias analyses. We used Monte Carlo simulations to detect the "age" effect given our measured effect size ($d = 0.281$). The goal was to determine whether the sample size was sufficient in previous experiments and to estimate the risk of alpha inflation at smaller sample sizes.

Monte Carlo simulations show no sign of alpha inflation for sample sizes used in the Thumser et al.[7] and Proudlock et al.[6] studies. However, they only showed power of 21 to 28% with these sample sizes. It is thus not surprising that they did not replicate each other's effects. Further Monte Carlo simulations suggest that sample sizes of 53, 90, and 142 per group are needed for 40, 60, and 80% power, respectively. This puts our sample size of 175 young and 482 old above that needed for achieving 80% power.

RESULTS

Distributions

Fig. 2 and Table 1 show the histograms for the main variables. Head-eye coefficient was bimodal. This was even clear for each nation, gender, age group, and across refractive correction levels (see below). Participants were thus classifiable as either "eye" movers (i.e., average HEC of 8.0 to 10.6, SDs of 2.7 to 5.6 across nations) or as "head and eye" movers (i.e., average HEC of 40.4 to 48.2, SDs of 20.0 to 24.4 across nations). For analysis purposes, we adopted a HEC cutoff of 25, corresponding to the trough between the two peaks. There was no evidence of a third population of

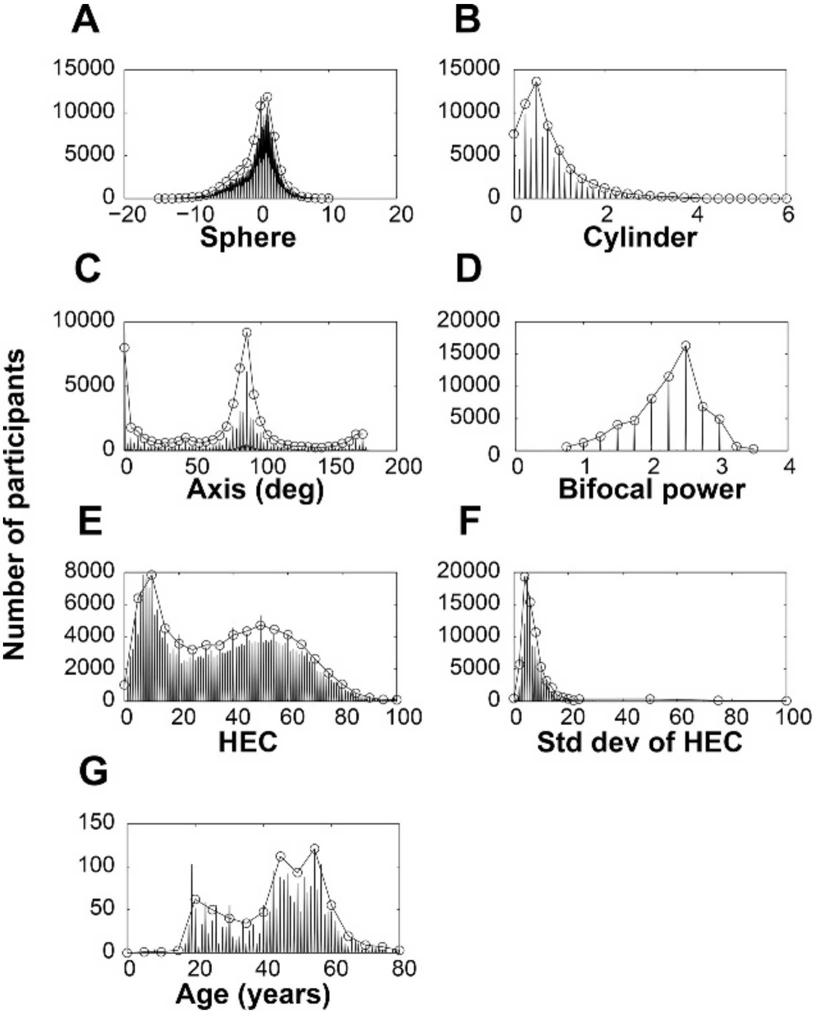

FIGURE 2.

Histogram plots for variables at two bin scales (fine scale, no symbol; broad scale, black circles): (A) sphere, (B) cylinder, (C) axis, (D) bifocal power, (E) HEC, (F) SD of HEC, and (G) age.

participants who primarily move their head without making significant eye movements in any of the distributions (transformed or not). Analyses below comparing mean HEC across categories reflect mainly differences in the relative heights of the two subpopulations: mainly eye movers versus even eye-and-head movers. Because of the difficulty and inaccuracy involved in estimating bimodal statistics, we opted to compare mean HEC using standard statistical methods (see Sample Size).

Age was also bimodal in our sample. For analysis purposes, we subdivided participants in two age groups: "younger" and "older," using the bimodal distributions as cutoff value (35 years old). Cylindrical axis was also bimodal with peaks at horizontal and vertical. Other variables were normally distributed with various degrees of skew.

Age and Eye Correction

Eye correction variables were intercorrelated in the full sample ($|r$ values$| > 0.104$, p values < 0.002) and in the laboratory sample ($|r$ values$| > 0.155$, p values < 0.002): near vision addition was

TABLE 1.

Summary statistics for the variables

	N	% Data	Mean ± SD	Median	Mode	Skew	Kurtosis
Sphere	57,861	88.9	−0.31 ± 2.74	0.1875	0	−0.77	4.15
Cylinder	57,861	88.9	0.78 ± 0.68	0.625	0.5	1.68	6.71
Axis	57,341	88.1	73.32 ± 46.83	85	0	0.00	2.60
Addition	61,285	94.1	2.25 ± 0.52	2.25	2.5	−0.79	4.16
HEC	65,115	100.0	36.19 ± 23.09	36	10	0.22	1.93
SD	65,060	99.9	7.60 ± 6.39	6	5	6.98	76.67
Age	657	1.0	44.27 ± 14.07	47	55	−0.33	2.40
Gender	621	1.0	57.0% male				

positively correlated with sphere and cylinder, and sphere and cylinder were negatively correlated together. Near vision addition was also correlated with HEC ($r = 0.1242$) and its SD ($r = 0.1527$), but only in the laboratory sample.

In the laboratory sample, age was correlated with gender ($r = 0.1353$, $p = 0.0152$), near vision addition ($r = 0.771$, $p < 0.002$), sphere ($r = 0.168$, $p < 0.002$), and HEC and its SD (r values = 0.209 and 0.159, respectively; p values < 0.002). Age was not correlated with cylinder ($r = 0.0968$, $p = 0.1659$).

Subdividing by age group (Fig. 3A), the older age group had a higher average HEC than the younger age group ($t = 3.59$, $df = 655$, $p = 0.0004$, $d = 0.281$). Young participants had no correction for near vision as expected.

Subdividing by near vision addition (Fig. 3B), there were significant HEC differences. The lowest addition power group had an average HEC similar to the two next addition power groups (t values < 0.877, $df \geq 12{,}707$, p values > 0.38, $d \leq 0.016$). All other differences were significant (t values > 2.83, $df \geq 6411$, p values ≥ 0.0047, $d \geq 0.071$) with a trend toward average HEC increasing with addition power. Overall, the age effect was evident in changes in the distributions, but the near vision addition effects were more subtle.

Additional effects supported a greater role of age than near vision addition. First, there was an age effect on HEC in participants who did not have correction for near vision (Fig. 3C; $t = 2.475$, $df = 284$, $p = 0.0139$, $d = 0.294$). Second, the effect of total correction on HEC was nonsystematic (i.e., there was no sign of a monotonic increase or decrease of HEC with total correction). Third, in the older age group, HEC did not vary as a function of addition (Fig. 3D; t values < 1.928, $df \geq 137$, p values ≥ 0.0546, $d \leq 0.212$). This can be taken as evidence that addition does not contribute independently to the HEC effect.

Together, this suggests that HEC is more closely linked to age than to correction and is only correlated to near vision addition inasmuch as addition is itself correlated to age.

Gender

Gender was only known for laboratory participants, which included Canadian, French, and Asian participants. Gender was

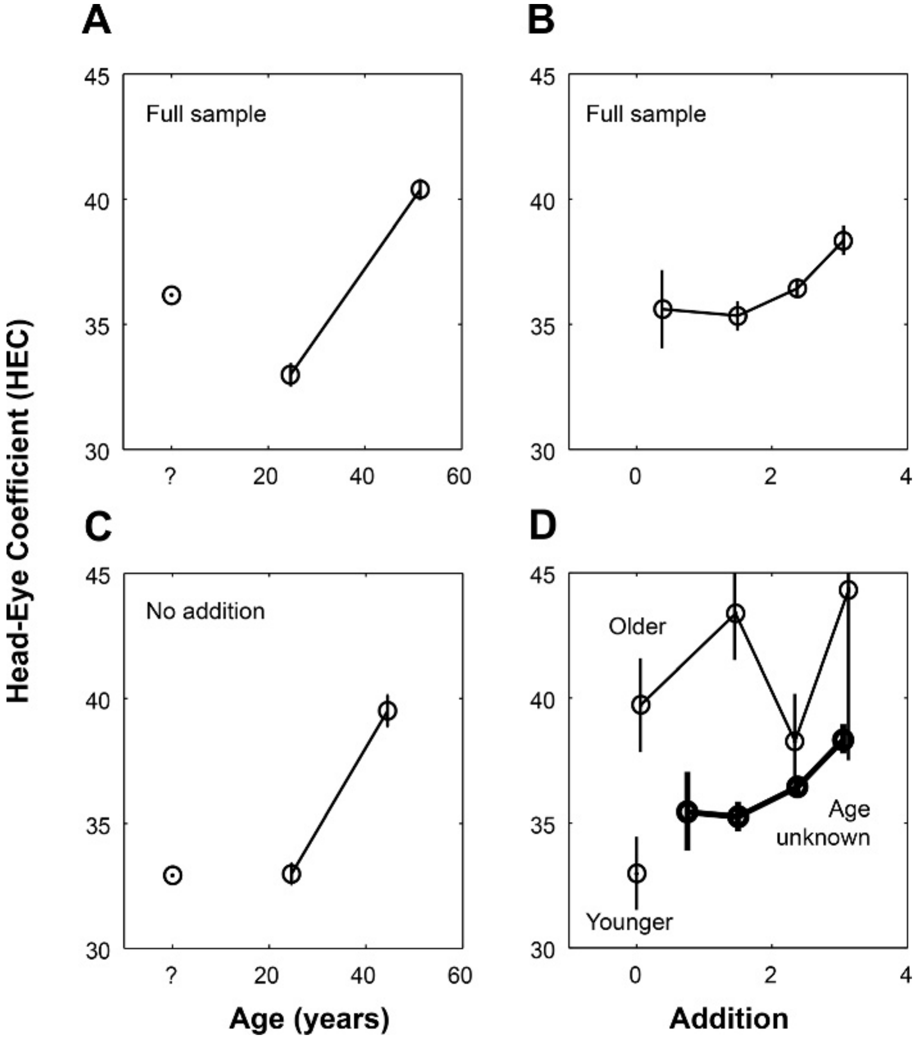

FIGURE 3.

Mean HEC for various subgroups. Participants were subdivided by age (A, C, and D) and/or correction (B to D). Specifically, panels show mean HEC as a function of (A) age, (B) addition (grouped by rounded value), (C) age for only participants without addition correction (younger n = 174; older n = 112), and (D) age and addition.

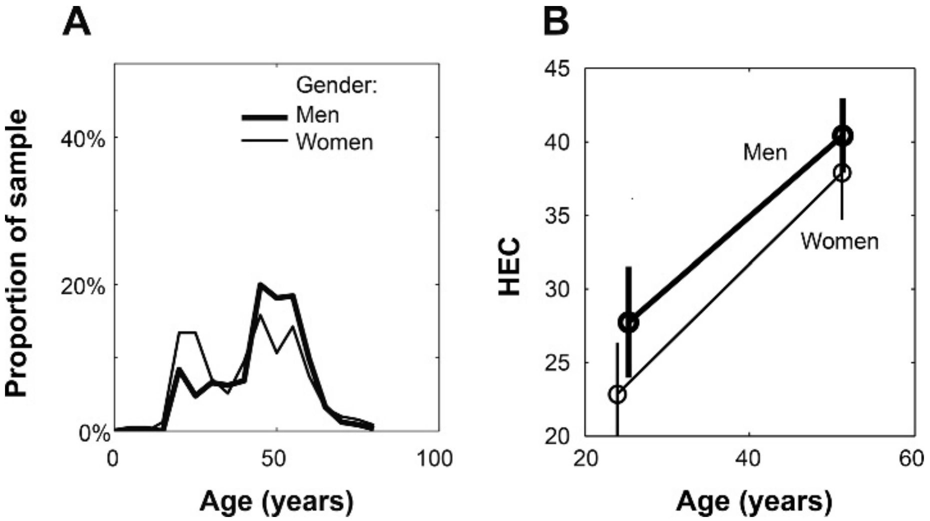

FIGURE 4.
(A) Age distribution of male and female subjects in our sample. (B) Head-eye coefficient as a function of age and gender (female, thin line; male, thick line).

known for 267 female and 354 male subjects. In our sample, male subjects were, on average, older than female subjects (Fig. 4A), although both age groups had at least 35% of each gender. Male and female subjects were equally likely to make head movements (ratios of eye-and-head movers to eye movers were 1.73× and 3.00×, respectively, see below for calculation details; $t = 1.6034$, $df = 619$, p = 0.1094, $d = 0.129$; Fig. 4B). We analyzed data by subdividing into subgroups based on age and gender for laboratory participants for whom both variables were known (Fig. 4B). Head-eye coefficient increased with age for both genders (t values > 2.469, $df \geq 265$, p values ≤ 0.0140, $d \geq 0.303$). There was no gender effect within age groups (t values < 0.952, $df \geq 173$, p values > 0.3420, $d \leq 0.145$).

Distributions by Nation

Data were subdivided by nation, for example, Canada, United States, Europe, and Asia (Fig. 5). The resulting HEC distributions were very similar across nations, except for the relative height or cumulative sum of the two modes. Using the cutoff (see METHODS), there were more eye-and-head movers by 1.34× for United States, 1.28× for Asia, 1.99× for Europe, and 3.80× for Canada. These differences were confirmed statistically: United States and Asia had similar average HECs (33.7 and 33.3, respectively; $t = 1.07$, $df = 29{,}422$, p = 0.28, $d = 0.012$) and all other average HECs differed from each other (t values > 3.75, $df \geq 4753$, p values < 0.0015, $d \geq 0.109$). The Caucasian laboratory sample had the highest average HEC (43.8) followed by EU (38.3). Therefore, it appears that the Caucasian laboratory had more eye-and-head movers, followed by Europe, with Asia and United States having similar proportions of eye-and-head movers.

Head-eye coefficient increased with age for both ethnicities for which age was known (i.e., Caucasians, Asians; t values > 2.825, $df \geq 238$, p values ≤ 0.0051, $d \geq 0.366$; Fig. 5). For both age groups, Caucasians did more head movements than Asians (t values > 3.801, $df \geq 173$, p values ≤ 0.0002, $d \geq 0.578$). Overall, the age effect on HEC is evident in both ethnicities, and the ethnicity effect on HEC is evident in both age groups. For the unknown age groups, Asians and US participants had similar amounts of head movements ($t = 1.558$, $df = 29{,}422$, p = 0.1192, $d = 0.018$), both lower than Europe (t values > 14.0, $df \geq 25{,}147$, p values < 0.0001, $d \geq 0.114$).

Stepwise regression analyses offer alternative explanations of the ethnicity effects by including other factors that differ across locations as potential predictor variables. Stepwise regression using latitude, longitude, log population density, per-capita gross domestic product (GDP), and two ethnicity variables (Asia vs. others; North America vs. Europe, with Asia = 0; see Tables 2 and 3 and Fig. 6) as predictors revealed that only GDP was a significant predictor of HEC ($r^2 = 0.492$, $F_{1,10} = 9.7$, p = 0.011; 95% confidence intervals of slope = 0.0826 to 0.5001; see equation 2), with only latitude nearing significance ($t = 2.04$, p = 0.072; all other variables $|t$ values$| < 1.01$, p values > 0.34). We suspected that the GDP effect may be related to geographic or political variables. Moreover, the GDP distribution was clearly bimodal, which violates normality assumptions in regression analysis. Our analysis included

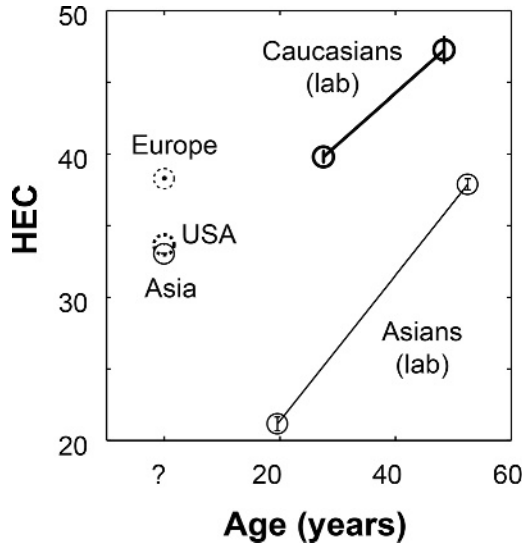

FIGURE 5.
Mean HEC as a function of age and location.

TABLE 2.

Data used for location-based analyses

	Latitude	Longitude	Population density/km^2	GDP per capita, $	Log density
United States	38	−77	34.2	52,839	1.534
Japan	35	139	337.1	37,135	2.528
Belgium	48	2	361.5	37,883	2.558
France	48	2	116	35,680	2.064
Spain	40	−3	92	30,128	1.964
Indonesia	−6	106	124.66	5182	2.096
Singapore	1	103	7540	50,323	3.878
Thailand	13	100	132.1	10,849	2.121
South Korea	37	126	501.1	33,156	2.700
India	28	77	375.7	3991	2.575
Montreal	45	−73	4517.6	43,349	3.655
Hong Kong	22	114	6544	52,687	3.816

a limited number of locations and may have lacked statistical power to evaluate the contributions of latitude or log population density. Therefore, we reanalyzed without GDP. Without GDP, latitude and log population density were significant predictors of HEC ($r^2 = 0.777$, $F_{2,9} = 15.7$, $p = 0.001$; 95% confidence intervals of slope = 0.1719 to 0.4239 and −1.0225 to 1.544, respectively; see equation 3; Fig. 6), and no other predictor was significant ($|t \text{ values}| \leq 0.54$, p values ≥ 0.608). The variance accounted for using these two variables exceeds that of GDP alone.

$$HEC' = 0.0002914 * GDP + 25.985 \qquad (2)$$

$$HEC' = 0.2979 * \text{Latitude} + 5.991 * \log(\text{Density}) + 11.1484 \qquad (3)$$

Bivariate correlations supported and explained this conclusion (Fig. 6; Table 3): (1) HEC was not correlated with race categories ($|r \text{ values}| \leq 0.397$, p values ≥ 0.202), (2) Asiatic nations were more southern ($r = -0.719$, $p = 0.008$) and eastern ($r = 0.927$, $p = 0.000$), (3) and HEC was correlated with latitude ($r = 0.621$, $p = 0.031$) but not longitude ($r = -0.320$, $p = 0.311$). Supporting the effect of latitude and not ethnicity, we note the following observations: (1) Asiatic nations at similar latitude as the European and North American nations had similar HECs, (2) the ethnicity effect observed above was mainly driven by the more southern Asiatic nations, and (3) all three ethnicities showed an increase of HEC with latitude, whereas GDP trends were inconsistent across ethnicities.

DISCUSSION

According to our analyses, HEC was linked to age, latitude, and log population density. Head-eye coefficient was not related to eye correction or gender. The effect of nation disappeared when controls were included. Thus, when VPS measurement is impractical, HEC can be estimated using age, latitude, and population density.

Arthritis predicts a reduction in head movements with age, but we observed the opposite effect. Our results are consistent with the reduction of oculomotor range with age,[33,34] where head movements would be made to compensate. However, there is no correlation between HEC and eye or neck range[4] or eye-saccade accuracy range.[5] A more plausible hypothesis is that the age effect may be attributed to failure to inhibit head movements.[6]

We reject the possibility that participants wearing glasses regularly and for longer would learn to make head movements to reduce aberration effects at the edge of glasses. Although participants were not wearing glasses during HEC testing, they could easily have learned habits with glasses that would transfer to cases where they are not wearing glasses. However, data were not consistent with the glasses-wearing hypothesis, as HEC was invariant with several measures of eye correction once age was corrected for. This lack of glasses effect is consistent with the results of Proudlock et al.[6] and generalizes the results of Stahl[14] to long-term glasses usage.

Our experiment measured head-eye coordination in a specific task. The lack of eye correction effect in both our task and previous studies[6,11–14] (but see Refs. [8,31]) suggests that our results should generalize to situations where participants wear their glasses; however, we have not tested this assumption directly. It is not clear whether our results will generalize to other tasks, for example, head-eye coordination during walking or driving or manual work. Our study also did not measure dizziness. To fully support our goal of reducing dizziness, further research is required to (1) generalize our results to other tasks; (2) establish a link between dizziness, HEC, and peripheral distortion; and (3) measure dizziness with and without VPS-corrected glasses.

Nation

US and Asian populations were equally likely to make head movements. Canadians and, to a lesser degree, Europeans were

TABLE 3.

Correlations between variables, with participants grouped by location (n = 12 locations)

	HEC	Latitude	Longitude	GDP	Log density	Eur vs. NA
Latitude	0.621*					
Longitude	−0.320	−0.592*				
GDP	0.701*	0.351	−0.330			
Log density	0.495	−0.191	0.245	0.413		
Race: Eur vs. NA	0.032	−0.180	−0.175	0.197	0.216	
Race: Asia vs. others	−0.397	−0.719†	0.927†	−0.365	0.308	0.154

The two race categories were as follows: (1) Asia versus others and (2) Europe versus North America, with Asia set at 0 (Eur vs. NA). These categories were chosen to be orthogonal.

*Significant at 0.05.

†Significant at 0.01.

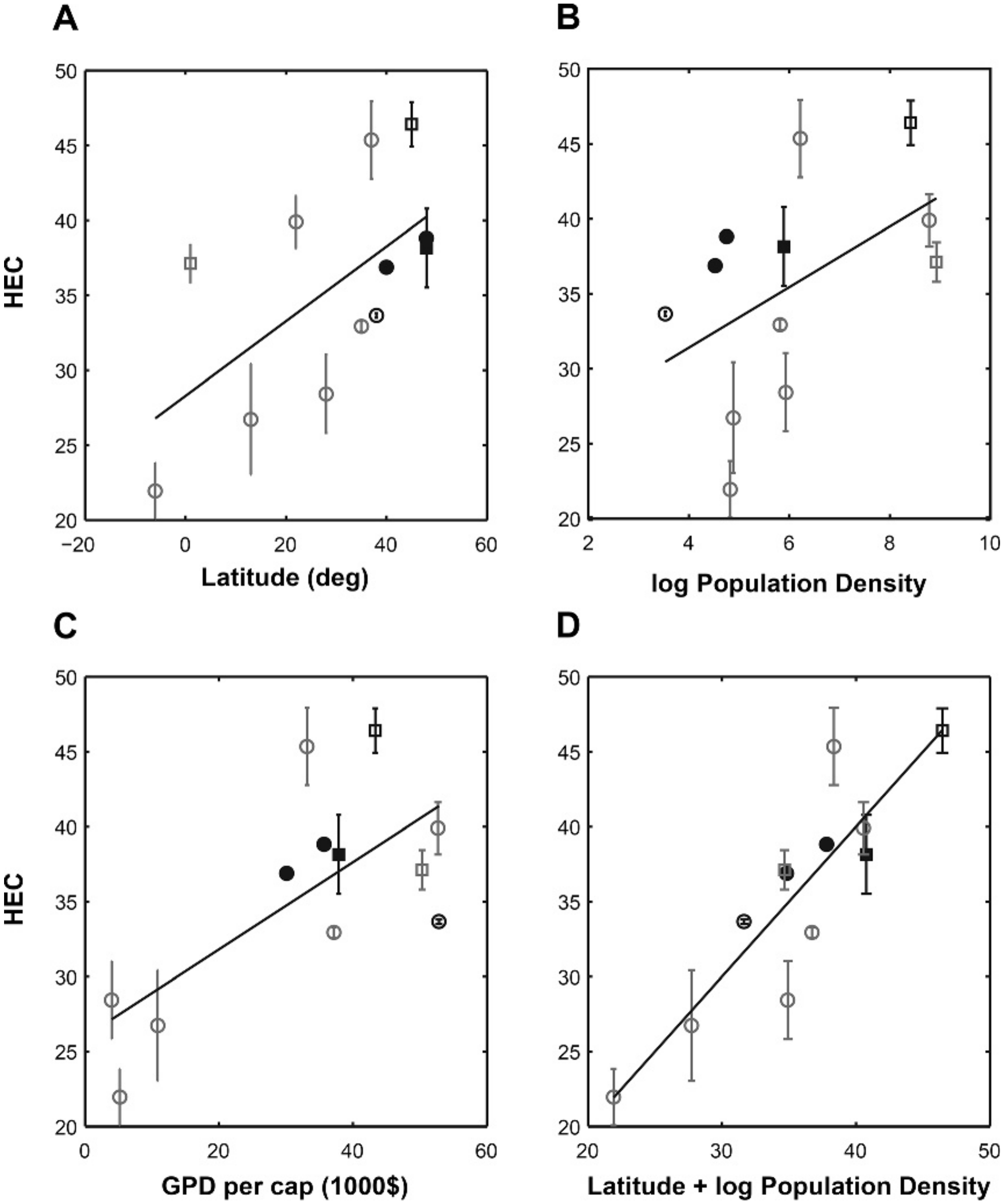

FIGURE 6.

Head-eye coefficient as a function of (A) latitude, (B) log population density, and (C) GDP per capita for each of the 12 subsamples. Laboratory samples are indicated by squares. Nations are North America (empty black symbols), Europe (filled black symbols), and Asia (empty gray symbols). Also shown in D is HEC as a function of latitude and log population density as analyzed jointly in a regression analysis.

more likely to make head movements. Experimental setting is unlikely to account for HEC score differences because (1) the effect was seen in both samples (i.e., laboratory and opticians) and (2) HEC scores are robust to large differences in methodology.[35] The literature on cultural differences in eye movements covers mainly differences between Asians and Westerners. We found a difference between Canadians, Europeans, and Asians, but not between Asians and Americans.

The most likely explanation is that HEC changes with latitude and population density, as our regression analysis shows. As ethnicities in our sample are distributed at different latitudes, and vary in population densities, this explains why ethnic effects were found when groups are split by ethnicity. At this point, we can only speculate as to why latitude or population density may be related to head movements. Potential explanations of this effect include weather, clothing differences (e.g., head movements may increase when wearing a hood over your head), living in urban versus rural environment (e.g., more head movements may be required to avoid getting hit by traffic, to find friends in a crowd), and so on. Further studies are required to establish the cause(s) of this difference.

We used ‘‘north’’ and ‘‘south’’ to discuss latitude; however, our sample only included participants in the northern hemisphere. If

HEC is linked to climate, then extrapolation predicts that participants in the south of the southern hemisphere (e.g., Australia, South Africa, and South America) should do more head movements during saccades compared with samples taken near the equator.

The sample included a correlation between latitude and longitude ($r = -0.592$, p = 0.042), meaning that locations were not spread around the world to properly disentangle effects of latitude and longitude. It is possible that sampling other locations could also help clarify the dependency of HEC on GDP, latitude, and log population density.

ACKNOWLEDGMENTS

This research was supported by an NSERC-Essilor industrial research chair and an NSERC discovery fund awarded to Jocelyn Faubert. The VPS system used in this study is manufactured by NIDEK and distributed by Essilor. Guillaume Giraudet is an employee of Essilor. Frédéric Poirier worked in Jocelyn Faubert's laboratory during this study.

Received June 15, 2014; accepted June 4, 2015.

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