Functional Assessment of Head–Eye Coordination During Vehicle Operation

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ABSTRACT: Purpose. Visual impairment, resulting from ocular abnormalities or brain lesions, can significantly affect driving performance. The impact of vestibulopathy on head–eye coordination is also a concern in vehicle operation safety, yet to date there has been little functional research in this area. An understanding of decrements in driving ability resulting from visual and vestibular pathology, plus the differences in visual strategies used by novice and experienced drivers, would benefit from an objective analysis of head–eye coordination during vehicle operation. Methods. We have developed a laptop-based system for measuring eye, head, and vehicle movement in real time. Digital video cameras mounted on lightweight swimming goggles are used to provide images of the eye and scene, allowing assessment of gaze. In addition, the use of inertial measurement units to simultaneously transduce head and vehicle movement allows us to evaluate the vestibular contribution to stable vision. Results. Data was obtained from a flight simulator and while driving a car. During banking turns in the flight simulator, there was a sustained roll tilt of the head and eyes toward the scene-derived visual vertical with a combined gain of approximately 25%. One of the most complex visual tasks when driving was exiting a multistory car park, which involved the scanning of hundreds of parked vehicles with an average fixation time of approximately 100 ms. The vertical vestibulo-ocular reflex was also found to make a significant contribution to the maintenance of dynamic visual acuity even while driving on paved surfaces. Conclusion. These results demonstrate the viability of functional assessment of head–eye coordination during vehicle operation, and potential applications of this technology to driver assessment are discussed. Analysis of both active and reflex contributions to gaze may provide a clearer understanding of the impact of visual and vestibular impairment on driving ability. (Optom Vis Sci 2005;82:706–715)

Key Words: head tracking, eye movements, vestibular, driving, flight simulator

Motor vehicle accidents account for 47% of accidental deaths and 94% of all transportation-related fatalities in the United States, and are the leading cause of death in the 1- to 33-year age group. The distribution of fatalities by age is bimodal, with both young (age range, 15–24 years) and older (75+ years) groups being most affected, and consequently much research has focused on the effects of the inexperience of novice drivers and on the sensorimotor, cognitive, and visual deficits associated with aging (see Wood for an extensive review). Driving is a vision-intensive task, and recent studies have demonstrated that age-related decrements in vision increase the probability of an accident, as determined from a statistical analysis of visual ability and driving records, and functional studies of road sign and hazard recognition on a closed-road circuit. Visual pathology is unlikely to be a major contributing factor to the increased fatality rate for the younger (age range, 15–24 years) group of drivers, but recent open-road studies have identified a more limited pattern of gaze fixations in novice drivers as compared with those with more experience. Thus, both visual function and the scanning techniques learned by drivers are important aspects of controlling an automobile.
oculography (EOG), in which surface electrodes measure variations in the electrical potential of the eye, and this technique has been used in flight simulator studies of pilot performance.\textsuperscript{15} EOG, however, has similar drawbacks to the IROG technique.\textsuperscript{14} Advances in image processing hardware has led to the development of automated noninvasive techniques for measurement of eye position using images from video cameras (video oculography [VOG]).\textsuperscript{16-27} Current commercial VOG systems use analog video cameras, requiring desktop computers with video acquisition cards to process eye movements, limiting their use in a real-world setting (e.g., Vision 2000, El Mar, Toronto, Canada; iView X, SMI, Teltow, Germany; ISCAN, Cambridge, MA). Moreover, the head-mounted cameras add significant mass to the head (300-g Vision 2000; 450-g iView X), which may impact operator behavior. Commercial VOG systems incorporating a scene camera to study gaze patterns have recently been used in flight simulator studies\textsuperscript{28} and for monitoring the gaze of pedestrians crossing an intersection\textsuperscript{29} (recording images to VCRs in the subject’s backpack) and walking through a complex indoor environment\textsuperscript{30} (with a 30-m umbilical cable).

An often neglected aspect of viewing behavior while driving is movement of the head. Two on-road studies have investigated one-dimensional head movement: head yaw (estimated from the position of a radio antenna in the scene image) in racing car drivers showed that subjects “steered” with their heads by pointing the naso-occipital axis into the turn,\textsuperscript{31} much like humans walking around a corner,\textsuperscript{32} and the magnitude of roll (lateral) tilt of the head into a turn (measured with an accelerometer) was related to road curvature.\textsuperscript{33}

Head movement is particularly relevant to the study of vestibular-related driving difficulties. The peripheral vestibular labyrinths sense angular and linear head movement, and this information is centrally processed to provide postural stability, compensatory eye movements (the vestibulo-ocular reflex), and awareness of body position in space (spatial orientation). Damage to the vestibular system may occur after head injury,\textsuperscript{34} viral infection of the vestibular nerve,\textsuperscript{35} minor strokes involving the anterior inferior cerebellar artery,\textsuperscript{36} use of ototoxic antibiotics (such as gentamicin),\textsuperscript{37} and surgical procedures. Age-related decrements in vestibular function are also well-documented,\textsuperscript{38,39} likely related to degeneration at both the peripheral\textsuperscript{40-42} and central\textsuperscript{43} level. Vestibulopathy is typically manifested as vertigo (sensation of spinning) and disturbed vision (inappropriate nystagmus, oscillopsia), often provoked by sudden head movement. For example, benign paroxysmal positional vertigo (BPPV), a common cause of dizziness,\textsuperscript{44} is thought to occur when small crystals of calcium carbonate (otoconia) from the utricular macula (the “linear accelerometers” of the vestibular labyrinth) migrate into the semicircular canal system. Changes in head position with regard to gravity, particularly in pitch or roll, trigger movement of the otoconia within the canal, generating vertigo and ocular nystagmus. In the acute phase of recovery after vestibular nerve sections or acoustic neuroma resections, patients often have brief episodes of vertigo during head rotations with associated blurred vision.\textsuperscript{45} In contrast, Ménière’s disease is characterized by sudden and unexpected attacks of vertigo usually unrelated to head movement.\textsuperscript{46}

Vestibular impairment engenders a substantial reliance on visual information to maintain balance and gaze, and a suppression of head movement to prevent vertigo and inappropriate ocular nystagmus, which may affect the ability of the individual to drive. Moreover, the vestibulo-ocular reflex (VOR), which acts to stabilize gaze by generating compensatory eye movements in the opposite direction to head movement, is critical in maintaining dynamic visual acuity while driving, because even the paved roads of urban centers generate high-frequency perturbations of the head. Clinicians in a number of countries have expressed significant concern with regard to vestibular disease and driving,\textsuperscript{47-50} although to date, there has been little functional research in this area. A recent study by Cohen et al\textsuperscript{45} assessed the impact of vestibular dysfunction on driving performance from subjective reports using a modified form of the Driving Habits Questionnaire developed for patients with visual impairment.\textsuperscript{9} The subject pool represented a broad spectrum of vestibular disorders, including BPPV, postoperative acoustic neuroma resections and vestibular nerve sections, Ménière’s disease, and chronic idiopathic vestibulopathy. These subjects reported considerable difficulty driving in reduced visibility (such as at night or during rain) and in visually complex environments (high-traffic roads, large intersections). Complex maneuvers involving spatial navigation such as changing lanes, staying in lane, and parking were problematic, likely as a result of impairment of path integration (i.e., summing of self and vehicle movement over time) that is degraded in vestibular patients.\textsuperscript{51} Vertigo and ocular nystagmus were also triggered by tasks requiring rapid head motion such as checking for traffic before changing lanes or entering an intersection or freeway on-ramp.\textsuperscript{45} The impact on stable vision can be devastating, because inappropriate nystagmus (i.e., not compensatory for head rotation) causes “spinning” of the visual scene.

Head–eye coordination is also critical in assessing the impact of visual field deficits as a result of ocular abnormalities\textsuperscript{52,53} (macular degeneration, glaucoma, or retinitis pigmentosa) or brain lesions (such as hemianopsia, a loss of vision in half of the visual field often related to stroke,\textsuperscript{54-56} or head trauma). Visual field loss does not affect visual identification but alters search strategies,\textsuperscript{57} with longer scan paths, more frequent and prolonged fixations, and consequently increased error.\textsuperscript{58} Transportation authorities in the United States and Europe typically require a minimum 120° horizontal field of view in the better functioning eye to obtain a driving license. However, recent studies have suggested that many patients who do not meet this criterion are able to drive safely with appropriate adaptation of head–eye coordination. Of 35 subjects with peripheral visual field deficits resulting from ocular disease (with a horizontal field extent limited to 84° on average), 15 (43%) passed an on-road driving assessment.\textsuperscript{52} Furthermore, patients who passed the test were found to have performed a greater number of head movements and began scanning earlier when approaching an intersection than those who failed. A similar study was recently performed with hemianopic patients whose visual field is typically limited to 90°.\textsuperscript{59} Training patients to perform frequent, large horizontal saccades into the blind hemifield, while minimizing head movement, generated a subjective enhancement of vision and measurable improvement in driving ability.\textsuperscript{59}

Analysis of head–eye coordination and vestibular contributions to visual behavior while driving is important in establishing standard operator performance, and for assessment of drivers with vestibular and visual field impairment. In this article, we describe a novel laptop-based system for simultaneous acquisition of three-
dimensional (3D) head, eye, and vehicle movement in real time. The system is comprised entirely of commercially available hardware and uses established VOG algorithms to accurately determine horizontal and vertical movements of the pupil, as well as rotation of the eye around the line of sight (ocular torsion). The portability of the system allows for the functional study of head–eye coordination and the vestibulo-ocular reflex in situations that were not previously possible, and as examples, we provide data obtained from a pilot operating an Airbus A340-600 motion simulator and from a subject driving a car in Manhattan.

METHODS

The experiments described subsequently were approved by the Institutional Review Board of the Mount Sinai School of Medicine and conformed to the Declaration of Helsinki. Informed consent was obtained from all subjects.

Hardware

The head–eye tracker was developed as part of a NASA-funded study of spatial disorientation in shuttle pilots and was implemented using commercially available components. Two “firewire” (IEEE 1394) digital cameras (Firefly; Point Gray Research, BC, Canada) were attached to lightweight swimming goggles (Aquasphere Seal, Genova, Italy) (Fig. 1A,B). The total weight of the headset was 146 g, significantly lighter than commercially available VOG goggles. A limitation of the current system is that spectacles cannot be worn under the goggles (although contact lenses can be used at the expense of torsional eye position measurement accuracy).

FIGURE 1.
A laptop-based video oculography (VOG) system for assessment of head–eye coordination during driving. (A) The subject wore goggle-mounted digital video cameras that imaged the left eye and the scene. An inertial measurement unit (IMU) was attached to the head band to measure head movement in space. The total weight of the headset was 146 g, which is considerably lighter than commercial VOG systems. (B) A second IMU was mounted to the vehicle to measure motion of the car in space. The video cameras and IMUs were connected to a laptop computer that provided eye, head, and car movement data and gaze-in-scene in real time, as well as generating digital video files for later display. (C) Screen dump from the laptop display during acquisition of data while driving in New York City. Color versions of Figures 1 through 6 are available at www.optvissci.com.

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The system was used to acquire eye, head, and cabin movement data aboard a full flight motion simulator (A340-600) at the Airbus training facility in Toulouse, France. Figure 2 shows roll head and eye movements during sustained (30 s) 45° banking turns during a fixed-base simulator run that modeled the heading alignment circle (HAC) maneuver during the final approach of the space shuttle. In response to the tilt of the visual horizon, a maintained tilt of the head of up to 5° (Fig. 2: lower panel, solid line), termed the optokinetic cervical reflex, although in this instance, is likely a combined optokinetic and optostatic response. In addition, there was a sustained torsional shift in eye position of 6° (Fig. 2: lower panel, dashed line), which preceded the head tilt. This ocular torsion was of similar magnitude to that produced by the gravity-sensing otoliths during a 45° head tilt with regard to gravity (ocular counterrolling [OCR]). It is important to note, however, that the OCR reflex would rotate the eye in the opposite direction to head tilt, whereas in this instance, both the head and eye rotated toward the scene-derived “visual vertical” (i.e., perpendicular to the horizon). Ocular torsion in response to a rotating visual line has recently been described, and this is, to our knowledge, the first account of sustained ocular torsion in response to a statically tilted scene. The combined head and eye roll tilt acted to orient the eye to the scene-derived visual vertical with a gain of approximately 25%.

Driving a Car

Data were obtained from an experienced subject (licensed 23 years) driving a midsized four-door sedan (2000 Chevrolet Cavalier LS) in daylight in a dense, urban environment (Manhattan). Figure 3 shows a sequence of images as the driver negotiated a series of 180° turns in a multilevel car park. The analysis software was set to output gaze fixations ±200 ms either side of the current scene image to allow complex scanning patterns to be represented in a static image. The subject scanned the reverse and brake lights on the rear of each parked vehicle ahead in a linear manner with a fixation time of approximately 100 ms per vehicle (i.e., on average four cars were scanned in each panel of Fig. 3, which represents a period of 400 ms). When a vehicle partially reversed into his path, the driver maintained fixation on the lit reverse indicator for a longer period (Fig. 3: panels 5 and 6) while continuing to scan the cars ahead. A similar scanning strategy continued when turning right from the car park onto the street (Fig. 4A). Other scanning
behaviors included checking the position of pedestrians while preparing to make a righthand turn (Fig. 4B), estimating the gap between two parked trucks before passing (Fig. 4C), reading an overhead road sign (Fig. 4D), fixating alternately on the tangent point of a curving road and the car ahead (Fig. 4E), scanning the rearview mirror and the road ahead (Fig. 4F), and checking the lefthand side mirror and a van in the driver’s blind spot before changing lanes to the left (Fig. 4G, H).

A novel aspect of our system is that it seamlessly provides synchronous head and vehicle movement data to augment the eye-in-head position data and gaze-in-scene. As the driver negotiated a twisting off-ramp from the George Washington Bridge (Fig. 5), both the fixation of the tangent of the curve and the roll tilt of the head into the turn are clearly shown, as described in two previous separate studies. The tilt of the head averaged approximately 10° into the turn (Fig. 5: lower panel, solid line), which was approximately half the angle of the gravito-inertial acceleration (GIA) tilt (Fig. 5: lower panel, dashed line). The magnitude of head and GIA tilt were similar to that observed in humans walking around a 0.5-m radius turn.

During unpredictable passive head movement, the vestibulo-

\[ \text{The vector sum of gravity and the centripetal acceleration of the car as it rounded the bend.} \]
ocular reflex (VOR) stabilizes gaze through compensatory eye movements. Figure 6 shows 15 s of head and eye pitch (rotation about axes parallel to the interaural axis) while driving along West 96th Street on Manhattan’s upper west side. Although this was a paved road in reasonably good condition, there was a continuous high-frequency pitching of the head (with peak-to-peak amplitude of approximately 6°) as a result of the vertical movement of the automobile over the uneven road surface (Fig. 6A: solid line). The pitch of the head, sensed by the semicircular canals, was used to generate vertical eye movements by the VOR that were of similar amplitude but in the opposite direction to head movement to maintain gaze (Fig. 6A: dashed line). A scatterplot of eye versus head position demonstrates this compensatory reflex with a linear regression showing a slope of close to unity (0.9) (Fig. 6B). Thus, the VOR is constantly generating compensatory eye movement to overcome passive perturbations of the head, which augments active gaze fixations to maintain stable vision when driving.

DISCUSSION

Driving a car is a visually complex undertaking, requiring integration of both active and reflexive head and eye movements to provide a stable view of the surroundings. Human head-eye coordination did not evolve to suit the high-inertial environment of powered vehicles, and these patterns of behavior must be learned, as evidenced by the limited scanning strategies of novice drivers. Moreover, visual impairment, which may not greatly affect active locomotion, can significantly diminish the acquired skill of automobile control. Obtaining functional measures of head-eye coordination during vehicle operation is an important aspect in understanding the basic visual strategies underlying driving, as well as assessment of the impact of visual and vestibular impairment on driving performance. Our laptop-based system allows the real-time analysis of 3D head-eye coordination that incorporates both ac-
tive head and eye fixation strategies, plus reflex contributions from the vestibulo-collic and vestibulo-ocular reflexes. The accuracy of the system is such that complex visual behaviors can be identified and quantified with a high temporal and spatial resolution.

To date, there has been little emphasis on the vestibular aspects of driving, at least in the functional sense presented here, but this is clearly an important issue. The VOR is continuously operational while driving, underpinning the active visual scanning strategies described here. Although patients with vestibulopathy may overcome decrements in VOR performance to some extent with pursuit and saccadic eye movements, this strategy breaks down in poor visual conditions or complex environments and during rapid head motion. As an example, the seemingly straightforward task of exiting a car park involves the methodical scanning of parked cars at rates of up to 10 per second (Fig. 3), which must be accomplished during rapid turns of the vehicle and the accompanying vestibular-generated head and eye movements to provide a seamless view of an environment with many potential hazards. A large number of drivers with vestibular impairment report significant difficulty in negotiating multistory car parks. Inappropriate ocular nystagmus, and therefore paradoxic motion of the visual surround, can be induced by activation of the semicircular canals during turns of the head and vehicle. In addition, the visual structure of car parks, which often have evenly spaced vertical columns or blinds to allow natural light, can present a challenge. Unfortunately, for drivers with vestibulopathy, the horizontal motion of these vertical structures while turning are akin to a rotating optokinetic drum and can themselves induce episodes of vertigo and optokinetic nystagmus.

The integration of gaze analysis with head and vehicle movement allows the evaluation of vestibular reflexes that maintain stable vision while driving. This may prove a useful adjunct to purely subjective forms of assessment of vestibulopathy on driving ability as well as addressing the larger question of what level of vestibular impairment is sustainable for safe driving. 

FIGURE 5.
A sequence of three scene images while negotiating a series of curves exiting the George Washington Bridge into Manhattan. The sequence of fixations 200 ms either side of each image are represented as dots. The head image below each scene shows the corresponding tilt of the head in vehicle coordinates (as viewed from behind the subject). The car image below the head shows the vector sum of gravity and the centripetal acceleration of the vehicle (the gravito-inertial acceleration [GIA]). The graph at the bottom of the figure shows head and GIA roll tilt data in vehicle coordinates, and the numbered cursors indicate the relative temporal location of the three frames. When cornering (frames 1 and 3), the driver fixated on the tangent of the curve. There was a large tilt of the GIA of approximately 20°, and a corresponding 10° roll tilt of the head, into the curve.

The optokinetic reflex generates ocular nystagmus in response to movement of the visual surround and shares many of the same neural pathways as the vestibulo-ocular reflex.
A detailed analysis of head–eye coordination and visual search strategies may also be of use in driver training. The more sophisticated scanning patterns of experienced drivers are presumably learned over many years on the road, and this information could be used in the instruction of novice drivers. This objective approach to teaching vehicle control based on the visual strategies of experienced operators has been evaluated by the U.S. Air Force and is currently being investigated by commercial aviation and NASA using the apparatus described here.

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