

Research Article

Disruption of Eye Movements by Ethanol Intoxication Affects Perception of Depth From Motion Parallax

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ABSTRACT—*Motion parallax, the ability to recover depth from retinal motion generated by observer translation, is important for visual depth perception. Recent work indicates that the perception of depth from motion parallax relies on the slow eye movement system. It is well known that ethanol intoxication reduces the gain of this system, and this produces the horizontal gaze nystagmus that law enforcement's field sobriety test is intended to reveal. The current study demonstrates that because of its influence on the slow eye movement system, ethanol intoxication impairs the perception of depth from motion parallax. Thresholds in a motion parallax task were significantly increased by acute ethanol intoxication, whereas thresholds for an identical test relying on binocular disparity were unaffected. Perhaps a failure of motion parallax plays a role in alcohol-related driving accidents; because of the effects of alcohol on eye movements, intoxicated drivers may have inaccurate or inadequate information for judging the relative depth of obstacles from motion parallax.*

The visual perception of depth is quick and effortless. Moving observers easily perceive the relative position of objects and obstructions through which they must navigate, and, because of their depth perception, generally accomplish this navigation successfully. For a moving observer, motion parallax is perhaps the most important visual cue to depth. However, surprisingly little is known about the visual system processes involved in the

perception of depth from motion parallax. In fact, it is unclear what information is necessary (S. Rogers & Rogers, 1992). Recent work suggests that slow eye movements have a central role in perception of depth from motion parallax (Nawrot, 2003a, 2003b). The current study investigated this possibility by disrupting slow eye movements through ethanol intoxication. If ethanol intoxication disrupts both slow eye movements and depth perception from motion parallax, this would be another indication that eye movements provide an important extraretinal signal required for the perception of depth from motion parallax. Moreover, this result might improve current understanding of why ethanol intoxication is a common factor in unsuccessful navigation with automobiles (Stapleton, Guthrie, & Linnoila, 1986).

Ethanol intoxication is known to have several rather selective effects on visual perception and eye movements. For instance, it degrades contrast sensitivity (Nicholson, Andre, Tyrrell, Wang, & Leibowitz, 1995; Pearson & Timney, 1998), but visual acuity and color vision remain largely unaffected (Hill & Toffolon, 1990; Wallgren & Barry, 1970; Watten & Lie, 1996). In addition, motion perception remains relatively unaffected (Bates, 1989; MacArthur & Sekuler, 1982; McNamee, Tong, & Piggins, 1980). Controversy remains regarding ethanol's effect on binocular stereopsis (Hill & Toffolon, 1990; Watten & Lie, 1996). Wegner and Fahle (1999) suggested that large interindividual differences and floor effects in previous binocular stereopsis studies hid very small, but significant, changes resulting from ethanol. Accommodation is not affected by ethanol intoxication (Watten & Lie, 1996).

Ethanol's effects on eye movements are well known. Ethanol intoxication slows the initiation and the velocity of saccadic eye movements and, most important, reduces the gain of slow eye movements (Holdstock & de Wit, 1999; Moser, Heide, &

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Kompf, 1998). Gain, the ratio of eye velocity to target velocity, should be very close to 1 if eye movements are to maintain fixation on a moving target. Intoxication reduces the velocity of slow eye movements, yielding a gain less than 1, and thereby requiring the visual system to recruit fast eye movement to generate a “catch-up saccade” (Baloh, Sharma, Moskowitz, & Griffith, 1979; Guedry, Gilson, Schroeder, & Collins, 1975). This produces the jerky eye movements, also called horizontal gaze nystagmus, that are observed during the field sobriety tests used by law enforcement (Belton, 1987; Forkiotis, 1986; Good & Augsburger, 1986; Kosnoski, Yolton, Citek, Hayes, & Evans, 1998; Mizoi, Hishida, & Maeba, 1969; Tiffany, 1986). Although it is well known that ethanol intoxication affects the gain of slow eye movements, recent studies from our laboratory suggest that these slow eye movements are crucial for the perception of depth from motion parallax. In the studies presented here, we sought to determine whether ethanol intoxication impairs the perception of depth from motion parallax through its influence on slow eye movements.

Motion parallax is created when an observer translates through the environment. During this translation, the visual system maintains fixation on a particular object by making a slow eye movement in the direction opposite the observer’s translation (Miles, 1993; Miles & Busettoni, 1992). This observer motion and compensatory eye movement create movement on the observer’s retina. Objects nearer than fixation, although remaining stationary in the environment, move on the observer’s retina in the direction opposite the observer’s translation. Conversely, objects farther away than fixation have retinal movement in the direction of the observer’s translation. Moreover, the retinal velocity of an object’s movement is proportional to the object’s distance from the fixation point, and the visual system uses this retinal motion for the perception of depth from motion parallax.

However, the retinal stimulus for motion parallax is inherently ambiguous, as there is no visual information to signal which direction of retinal motion corresponds to near or far depth. To solve this ambiguity, the visual system may rely on extraretinal information to determine the depth sign. Using a motion aftereffect technique designed by Ono and Ujike (1994), Nawrot (2003b) was able to demonstrate that head movement and vestibular-ocular response do not provide this information; rather, the necessary extraretinal information is provided only by the visually driven early or direct component of the optokinetic response (OKRe; Miles, 1993; Miles & Busettoni, 1992) eye movements. It also appears that the gain of OKRe eye movements influences how perceived depth from motion parallax is scaled with viewing distance (Nawrot, 2003a).

Although it is important to know whether ethanol has an effect on the perception of depth from motion parallax, this study also addressed a more fundamental issue regarding slow eye movements by separating the role of such movements’ efferent signals from the purely visual information that drives the eye

movements. That is, the data bear on the question whether motion parallax relies on retinal-slip information or information about the efferent eye movement motor signal being planned and executed in the brain. Consider that slow eye movements, both smooth pursuit and OKRe, are generated in response to retinal slip of a target or fixation point on the retina. Slow eye movements minimize the slip by pursuing the target. They are not generated in the absence of such retinal slip. Given that ethanol intoxication reduces the efferent motor signal and thereby increases the retinal-slip signal, any deficit in the perception of depth from motion parallax caused by ethanol intoxication suggests that the visual system uses the efferent motor signal, not a retinal-slip signal, for perceiving motion parallax.

A final consideration is that for motion parallax created by abrupt translation of the observer’s head, the eye movements have two different components, the effects of which need to be separated. If motion parallax is generated by the observer’s head translation along the interaural axis (side to side), then the translational vestibular-ocular response (TVOR) generates the primary compensatory eye movement signal to maintain fixation during the head translation. However, with near viewing distances, TVOR typically undercompensates (i.e., has a gain less than 1), thereby creating retinal slip and conditions that elicit an additional OKRe eye movement signal to maintain perfect fixation (Miles, 1993; Paige & Tomko, 1991; Schwarz & Miles, 1991). In cases of large viewing distance and sustained passive movement of the observer (such as when the observer is riding in an automobile), vestibularly driven eye movements are absent, and fixation is maintained with pursuit or OKRe eye movements alone. It is these fixation-maintaining eye movements, which occur in every instance that depth from motion parallax is perceived, that are central for the perception of depth from motion parallax (Nawrot, 2003b). The TVOR eye movements are not directly involved in the perception of depth from motion parallax. Although the effects of ethanol intoxication on the canal-driven rotation vestibular-ocular response (RVOR) and visual-RVOR interactions are well known (Barnes, 1984; Barnes, Crombie, & Edge, 1985; Barnes, Eason, & Eldridge, 1988; Harder & Reker, 1995), there is no known effect of ethanol intoxication on the otolith-driven TVOR.

METHOD

Participants

Fifteen paid participants, who met stringent inclusion criteria, were selected from 30 initial volunteers. Inclusion criteria included being over the age of 21, having a body mass index (BMI) between 20 and 30, and performing perfectly on our visual screening. In addition, volunteers were included only if they indicated they had no mental, neural, ocular, or general health problems; had no family history of alcoholism; were not problem drinkers or nondrinkers; and were not pregnant. The

participants included 9 males and 6 females with an average age of 24 years and an average BMI of 25. All participants were right-handed.

Materials and Measures

Basic vision screening included acuity, Pelli-Robson contrast-sensitivity (Clement Clarke, Columbus, Ohio), and Stereo-Randot and Stereo-Fly tests (Stereo Optical, Chicago, Illinois). Psychophysical tests were computer generated, with visual stimuli presented on a computer monitor; computer interaction with eye-tracking, head-tracking, and stereoscopic viewing devices was accomplished through a 12-bit multifunction analog-to-digital board with digital input and output (National Instruments, Austin, Texas).

Depth Perception

The stimuli for all tests were computer-generated random-dot patterns. These patterns depicted a corrugated surface undulating in depth because of either motion parallax or binocular-disparity information (B.J. Rogers & Graham, 1979). In all tests, observers performed a two-alternative forced-choice task, making a decision regarding the phase of depth depicted by the stimulus. The magnitude of depth depicted was varied in successive trials using a staircase procedure to estimate the 79%-correct threshold (Wetherill & Levitt, 1965).

For binocular disparity, stereo stimuli were presented to the two eyes through a 33-Hz frame-sequential presentation using ferro-electric shutters (Displaytech, Longmont, Colorado) mounted in trial frames worn by the observer. The shutters have a 70- μ s transition and a 1,000:1 contrast ratio between on and off states. At a viewing distance of 342 cm, a minimum binocular disparity of 20 arcseconds was achieved, while the entire random-dot stimulus subtended $2.2^\circ \times 2.2^\circ$.

For motion parallax, observers moved their head along the interaural axis, with their head in a rest that translated along a linear head-tracking device. Observers typically made head movements at a rate between 0.5 and 1 Hz. The head-tracking device used a linear potentiometer (ETI Systems, Carlsbad, California) with a 20-cm slide translation and measurement linearity (r^2) of .999. The head rest minimized head movement in the other five dimensions, but required only about 1 N to translate laterally. Every 15 ms, head position was measured to the nearest 0.1 mm, and changes to the random-dot stimulus were made: Dots intended to appear nearer than the fixation point were shifted in the direction opposite the head movement, and dots intended to appear farther away than the fixation point were shifted in the direction of the head movement; dots with zero depth (e.g., the fixation depth) remained unchanged. Intermediate dots were shifted in accordance with a vertical sinusoidal function, thereby creating the appearance of a corrugated surface fronto-parallel to the observer (B.J. Rogers & Graham, 1979). Magnitude of the depicted depth was controlled

by varying the relationship between the extent of peak stimulus dot movement and observer's head movement. This relationship is called disparity equivalence and is quantified as the magnitude of peak dot movement for a head movement of 6.5 cm (typical interocular distance), thereby equating it with binocular disparity with this interocular separation. The random-dot stimulus subtended $13.4^\circ \times 13.4^\circ$ at a viewing distance of 57 cm.

Although the stereoscopic and motion parallax stimuli were presented at different viewing distances (342 cm vs. 57 cm) and had different overall retinal size ($2.2^\circ \times 2.2^\circ$ vs. $13.4^\circ \times 13.4^\circ$), the retinal stimuli were made as similar as possible. In both kinds of stimuli, dots (1,000 for stereopsis and 10,000 for motion parallax) subtended 2 arcminutes \times 2 arcminutes, and the sinusoidal depth corrugation had an optimal frequency of 0.4 cycles per degree of visual angle (B.J. Rogers & Graham, 1982).

Pursuit Eye Movements

Eye movements were measured with a head-mounted infrared limbus eyetracker (Skalar, Delft, The Netherlands) recording from the right eye at 67 Hz. The left eye was occluded. Eye movements were measured while observers viewed a small dot that traversed 20° across the computer monitor, following a sinusoidal velocity pattern with a peak of $22^\circ/\text{s}$. For each recording, pursuit gain was determined by comparing instantaneous eye velocity and target velocity for the central 12° of the display, thus excluding the last few degrees, when both eye and target were reversing. If eye velocity matched target velocity, then pursuit gain was close to 1. If eye velocity was less than target velocity, then pursuit gain was less than 1.

Compensatory Eye Movements

Eye movements are generated to compensate for head translations along the interaural axis. These compensatory eye movements have both a vestibular component (TVOR) and a visual component (OKRe or pursuit). To separate them, we measured eye movement gain during observer head translation in both light (TVOR + OKRe) and dark (TVOR) conditions. In the light condition, a small fixation target was visible to observers during the head translation. In the dark condition, the visual fixation target was extinguished, and the computer monitor was occluded the moment observers began their head movement, leaving the room totally and immeasurably dark. The infrared eyetracker could measure observer eye movements in complete darkness while producing no visible light.

In the light condition, observers were instructed to maintain fixation on the target while making head translations. In the dark condition, observers were instructed to maintain fixation on their remembered or imagined position of the target. Eye and head movements were recorded for 6.5 s and included two to three cycles of observer head movement. Immediately following each trial with the fixation spot visible, the observer repeated the procedure in a dark-condition trial. Observers made four to

five recordings (trials) to ensure that at least one or two were suitable for analysis. Exclusion criteria for each trial included having a calibration r^2 value less than .96 and a gain value greater than 1.5 or less than 0.5 ($\pm 3 SD$), which would indicate the observer failed to perform the task or moved excessively between calibration and recording.

Gain in both the light and dark conditions was determined by regressing eye movement on head movement for the central 7° to 10° of translation. Because the recording rate was fixed, the number of points included in the analysis depended on how fast the observer's head moved. The slope of the regression gave the gain of the eye movement for the accompanying head movement. The average gain for each trial was determined from four translations, two to the left and two to the right. OKRe gain was determined by subtracting average gain in the dark condition (TVOR) from average gain in the light condition (OKRe + TVOR).

Ethanol Intoxication and Measurement

In the intoxicated condition, observers were administered ethyl alcohol (as a mixture of 100-proof vodka and orange juice) at 0.8 g per kg body weight, to achieve a blood alcohol content (BAC) approaching 0.1%. The total ethanol administration was divided into four equal doses given in 10-min intervals. BAC was assessed by breath analysis using an Intoxilyzer 5000 (CMI, Inc., Owensboro, Kentucky), a common evidentiary breath analyzer using infrared absorption. It typically has good agreement with venous blood analysis (Jones, Beylich, Bjorneboe, Ingum, & Morland, 1992). Calibration was checked with a wet-bath alcohol breath simulator (Toxitest Model ABS 120, CMI, Inc.). Secondary BAC measurements were made with a Lifeloc FC10 (Lifeloc Technologies, Inc., Wheaton Ridge, Colorado) breath analyzer that uses a fuel-cell electrochemical sensor to measure breath ethanol. BAC measurements were made every 10 min throughout the study.

Motion Perception

Although research suggests that motion perception is not affected by ethanol intoxication (Bates, 1989; MacArthur & Sekuler, 1982; McNamee et al., 1980), a subset of 9 subjects completed a simple motion-direction discrimination task (see Nawrot & Rizzo, 1995, for details) using random-dot stimuli. The task was to indicate the direction of signal-dot motion (four-alternative forced choice) within a randomly moving noisy background. Motion perception thresholds were determined by probit analysis.

Procedure

A repeated measures within-subjects design was used to assess the effect of ethanol intoxication on eye movements and the perception of depth from motion parallax. Upon passing the screening requirements, subjects first completed the psycho-

physical tests in the nonintoxicated (sober) condition. Psychophysical tests proceeded in the same order in both the sober and intoxicated conditions: binocular disparity, motion parallax, pursuit eye movements, compensatory eye movements in light and dark, and motion perception. Within a few days of completing the tests in the sober condition, subjects returned to complete them in the intoxicated condition. This order was not randomized, as the introduction of a novel task to an intoxicated observer might add considerable variability to the data, possibly leading to an overestimation of ethanol's effect. To maximize ethanol absorption, we asked subjects to refrain from eating for 4 hr prior to the study. Subjects were also required to have a BAC of 0.0 before the ethanol administration. Psychophysical tests began 20 min after administration of the last ethanol dose. If the observer's BAC was less than 0.08%, we allowed 10 min more for the BAC to rise before psychophysical testing began. Following the study, subjects remained in the lab until their BAC was below 0.05%. They were given taxi rides home and asked to remain at home for an additional hour.

RESULTS

BAC

Starting BAC in the intoxicated condition averaged 0.085% ($SE = 0.01\%$) and ranged between 0.07 and 0.14%.

Pursuit Eye Movements

The top panels of Figure 1 show typical eye movement recordings from a sober and an intoxicated observer. The middle panels of the figure show the velocity of the eye movements graphed in the top panel. A comparison of the panels shows that the intoxicated observer's eye velocity is lower than that of the sober observer and is most obviously lower following the second cycle. Because of the low eye velocity, many more high-velocity saccadic eye movements are made. These spikes reflect the recruitment of the fast saccadic eye movement system to jerk the eyes into a position to regain pursuit of the target. They are indicative that the slow eye movement signal was insufficient to maintain adequate pursuit. The lower panels of Figure 1 show the ratio of eye to target velocity (gain). Gains for the sober trials were close to 1 ($M = 0.92$, $SE = 0.02$; gain = 0.97 in the example shown in Fig. 1), showing very accurate visual pursuit of the target. Gain values for the intoxicated trials were typically below 1 ($M = 0.67$, $SE = 0.04$; gain = 0.68 in the example shown in Fig. 1), showing very poor visual pursuit of the target. As expected, ethanol intoxication significantly reduced eye movement gain, $t(14) = 4.64$, $p < .001$, $d = 1.24$.

Compensatory Eye Movements

Figure 2 shows typical head and eye movement recordings for an intoxicated observer making lateral head translations. Although the head and eyes move in opposite phase, the

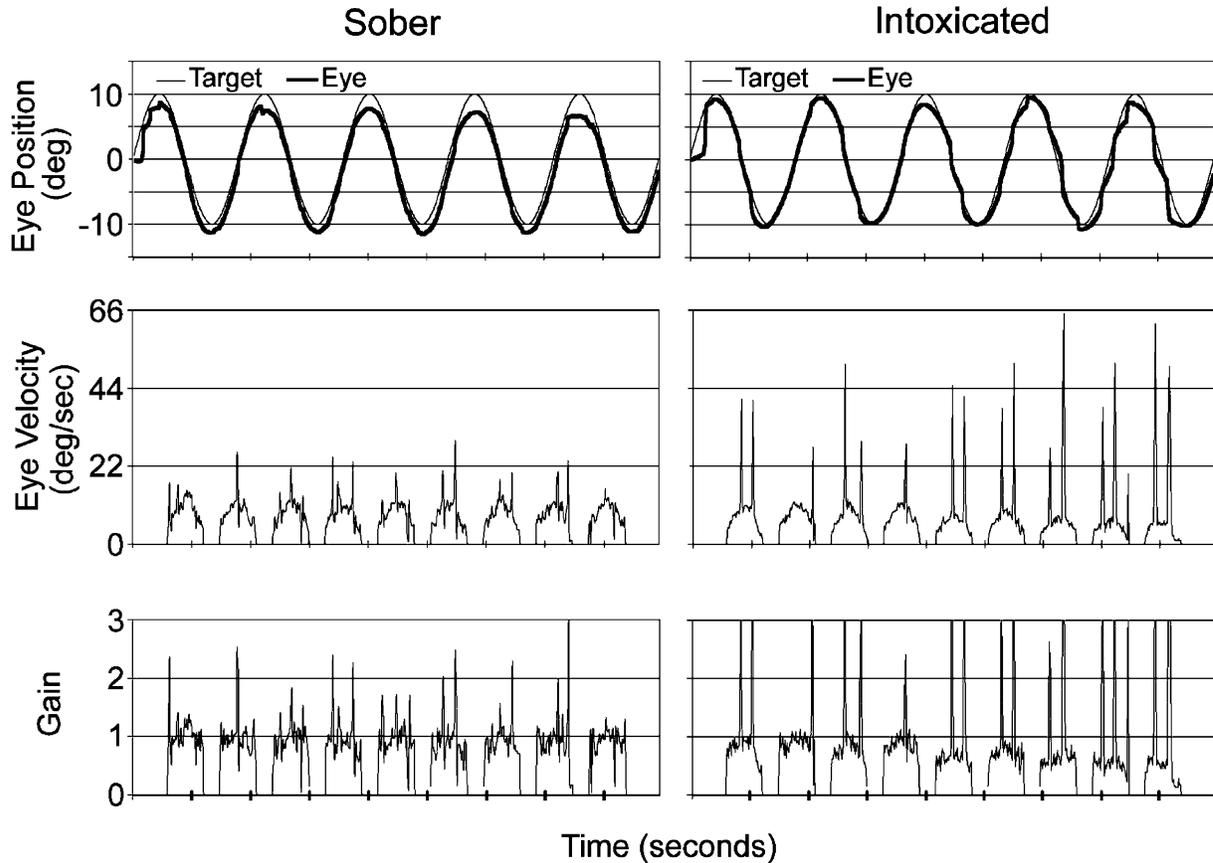


Fig. 1. Example of visual pursuit of the sinusoid target by a sober observer (left column) and an intoxicated observer (right column). The graphs in the top row show horizontal eye and target position as a function of time. The graphs in the middle and bottom rows show the corresponding eye movement velocities and gain values (eye velocity/target velocity), respectively.

recordings are shown in phase to aid comparison. Recordings for sober observers were similar, but smoother. The top panel shows data from recordings made when the fixation spot was visible. The bottom panel shows data from recordings made when the intoxicated observer was in complete darkness and maintained fixation on an imagined spot. Figure 3 shows the average gain values for 11 observers who generated at least one trial that could be analyzed in each of the four conditions (sober and intoxicated, light and dark). Gain in the dark condition (TVOR alone) was not affected by ethanol, $t(10) = 0.89$, $p = .20$, $d = 0.27$. Thus, the significant reduction of gain in the light condition (TVOR + OKRe) among intoxicated observers relative to sober observers, $t(10) = 1.84$, $p = .04$, $d = 0.55$, was due to a specific reduction in OKRe, not due to a change in TVOR. Therefore, like the gain of pursuit eye movements, the gain of the OKRe component of compensatory eye movements was affected by ethanol intoxication; however, the TVOR component was unaffected.

Motion Parallax and Stereopsis

Figure 4 shows average thresholds for the motion parallax and stereopsis depth perception tasks. Although thresholds were

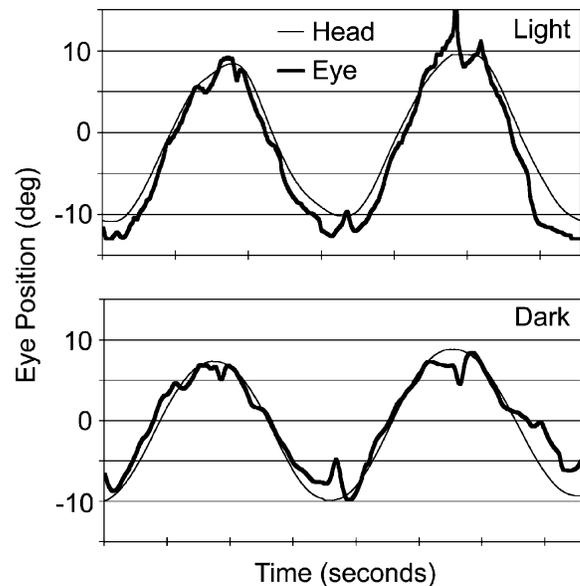


Fig. 2. Typical head and eye movement recordings for an intoxicated observer who attempted to maintain fixation on a target during lateral head movement. In the light condition (top), the target was visible. In the dark condition (bottom), the observer was in complete darkness and imagined the target.

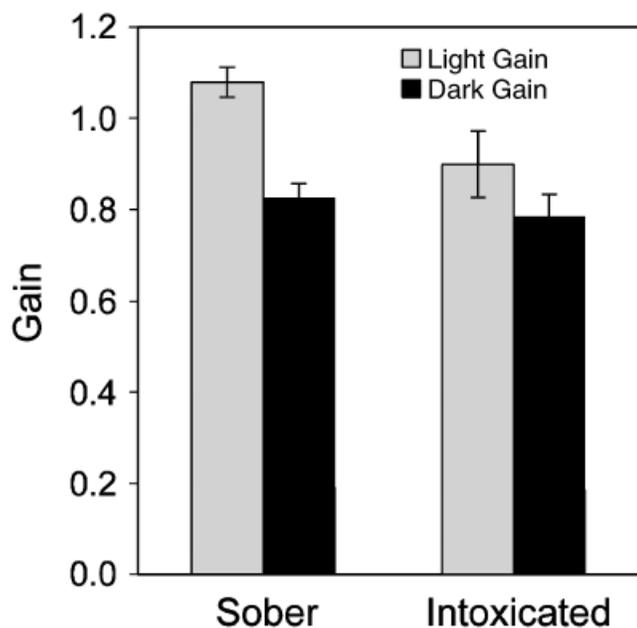


Fig. 3. Average gain of compensatory eye movements in the light and dark conditions as a function of sobriety. The values graphed are based on data from 11 observers who produced at least one trial that could be analyzed in each of the four conditions.

generally consistently low, thresholds for individual intoxicated observers covered a wide range in the motion parallax task, as illustrated by the large error bars. Ethanol intoxication raised the average observer thresholds for motion parallax, $t(14) = 3.15$, $p = .004$, $d = 0.81$, even though thresholds for 5 of the 15 observers were not affected by the ethanol intoxication, remaining at the test floor of 30 arcseconds. However, these

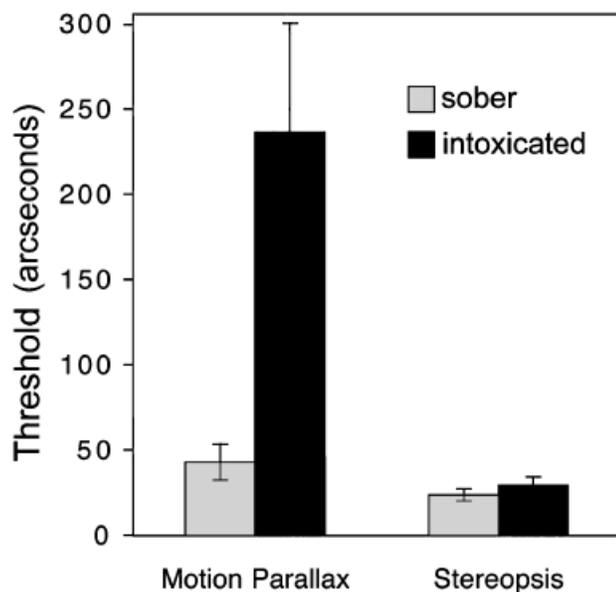


Fig. 4. Average thresholds of sober and intoxicated observers in the motion parallax and stereopsis depth perception tasks (± 1 SE).

observers did report that in the intoxicated condition they experienced increased difficulty performing the motion parallax task, the perceived depth appeared more ambiguous, the stimulus had perceptual reversals during a trial, and they saw movement of the stimulus dots rather than rigid corrugations. These observers did not differ from other observers in BAC (0.086%) or in pursuit eye movement gain (0.73). Unfortunately, the information collected on individual drinking histories (to exclude nondrinkers and problem drinkers) is insufficient to address whether drinking history was a source of variability in the motion parallax test. For binocular stereopsis, no threshold elevation was seen in the intoxicated condition, $t(14) = 1.71$, $p = .055$, $d = 0.44$, as all observers remained at or close to the test floor of 20 arcseconds. Insofar as the similarities in the motion parallax and stereopsis tasks and thresholds allow comparison, the interaction between depth cue and intoxication depicted in Figure 4 is significant, $F(1, 14) = 9.11$, $p = .009$, $\eta^2 = .39$.

Motion Perception

As expected on the basis of previous work (MacArthur & Sekuler, 1982), thresholds on the motion perception task were not affected by ethanol intoxication, $t(8) = 0.872$, $p = .204$, $d = 0.22$. Therefore, the change in motion parallax thresholds was most likely caused by a change in OKRe gain rather than a change in the perception of visual motion.

DISCUSSION

It is well known that pursuit and OKRe eye movements are disrupted by ethanol intoxication. These disrupted eye movements have a demonstrable effect on the perception of depth from motion parallax. In the present study, depth perception was not generally affected by ethanol, because thresholds for the binocular stereopsis task remained unchanged in the intoxicated condition. Similarly, motion perception was not affected by ethanol; these thresholds remained unchanged as well. Moreover, ethanol intoxication did not affect TVOR eye movements, which do not play a role in the perception of depth from motion parallax but interact with the OKRe eye movements that do have an important role in motion parallax (Nawrot, 2003b). Our conclusion is that ethanol affected the slow, OKRe eye movements and the perception of depth from motion parallax that relies on these eye movements.

These results underscore the importance of OKRe eye movements in the perception of depth from motion parallax. It appears that the visual system uses these eye movements as an extraretinal signal to disambiguate the depth order of motion parallax. For binocular disparity, the discrimination between crossed and uncrossed disparity is achieved by cortical neurons that detect the phase relations of visual information on the two retinas (Ohzawa, DeAngelis, & Freeman, 1990). However, for

motion parallax, the visual information is ambiguous, and extraretinal information is required to disambiguate the depth order of the opposing directions of retinal motion. The slow eye movement system provides this extraretinal signal, and disrupting this system interferes with the perception of depth from motion parallax.

To further clarify the role of OKRe eye movements in motion parallax, this study separated the roles of retinal slip and efferent motor signals. As eye movement gain decreased with ethanol intoxication, retinal slip increased, but did not produce any advantage for the perception of motion parallax. This result reinforces the proposal that the signal needed for motion parallax is not retinal slip, but an extraretinal, efferent-copy signal. Of course, it must be determined if the effect on motion parallax was due specifically to the change in OKRe signal, or whether the recruitment of the saccadic eye movement system caused an interruption in the available OKRe signal, thereby affecting the perception of depth from motion parallax.

This deficit in slow eye movements might have even broader implications for the perception of heading direction from motion parallax (Cutting, Springer, Braren, & Johnson, 1992; Frey & Owen, 1999). Cutting, Alliprandini, and Wang (2000) found that moving observers determine heading direction by making saccadic eye movements around the scene in an attempt to find and fixate the optimal points providing visual information about the direction of travel. Slow eye movements are required to maintain fixation on this primary informative region because it lies off the moving observer's direction of travel. Now, consider that ethanol intoxication not only disrupts the slow eye movement system, but also slows the initiation of saccadic eye movements (Holdstock & de Wit, 1999). It may be important to determine if ethanol intoxication interferes both with the fast eye movement search for points that provide heading information and with the maintenance of fixation on these points so that the information used for heading determination can be perceived. Indeed, the effects of ethanol intoxication on eye movement may have an underappreciated impact on the visual mechanisms necessary for successful locomotion through a cluttered and hazard-filled environment. Although the current study suggests that intoxicated drivers may have difficulty determining the relative position of obstacles using motion parallax, this may be only one part of a broader, but poorly understood, set of visual perceptual problems caused by ethanol's effect on the eye movement system.

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