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Risky Driving Behavior: A Consequence of Motion Adaptation for Visually Guided Motor Action

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The authors examined the effect of adaptation to expansion on overtaking maneuvers in a driving simulator. Following driving on a straight empty road for 5 min, drivers initiated overtaking substantially later (220–510 ms) than comparable maneuvers made following viewing a static scene or following 5 min of curve driving. Following adaptation to contraction (produced by driving backward), observers initiated overtaking significantly sooner. The removal of the road texture significantly reduced the size of the adaptation effect. The authors propose that these changes in overtaking behavior are due to misestimation of the time headway produced by local adaptation of looming detectors that signal motion-in-depth for objects near the focus of expansion. This adaptation effect may increase the risk of rear-end collisions during highway driving.

Prolonged viewing of a visual stimulus can produce perceptual changes in a subsequently viewed stimulus (Swanston & Wade, 1994) that are often specific to a particular dimension of the adapting stimulus. For example, in the familiar waterfall illusion, extended inspection of the downward flow of water causes the perceived motion but not the color or size of a subsequently viewed object to be altered. This ability to selectively adapt the human visual system has been used as a psychophysical tool to investigate many different types of perceptual processing, including spatial frequency (Blakemore & Campbell, 1969), orientation (Blakemore & Nachimas, 1971) and motion (Pantle & Sekuler, 1968; Regan & Beverley, 1978). It has also been instrumental to our understanding of general perceptual phenomena such as opponent processing (e.g., Boynton, 1979) and visual information channeling (reviewed in Regan, 1982). But, does selective adaptation of the visual system have any important effects on our behavior in the world outside the laboratory? We now consider one situation where selective adaptation to motion could have a detrimental effect on a common visually guided motor action.

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Overtaking and Passing Maneuvers on the Highway

One of the most dangerous situations faced by a car driver is overtaking and passing a moving vehicle. The driver must estimate the time to collision with oncoming cars and judge whether there is sufficient time to complete an overtaking maneuver, while simultaneously monitoring the lead car so as to avoid a collision. Furthermore, this task is often made even more difficult because hills or fog can reduce the visibility of oncoming traffic. Indeed, Jeffcoate, Skelton, and Smeed (1973) reported that on British roads in 1972 about 15% of injury-causing automobile accidents involved an overtaking vehicle.

One source of time to collision (TTC) information available to the driver in this situation is shown in Equation 1:

$$\mathrm{TTC} \approx \frac{\theta}{(d\theta/dt)}, \tag{1}$$

where θ is an approaching car's instantaneous angular subtense and $d\theta/dt$ is its instantaneous rate of increase of angular subtense (Hoyle, 1957). It has been suggested that drivers use Equation 1 (and its first temporal derivative) to control the rate of deceleration when braking behind a lead car (Lee, 1976; Yilmaz & Warren, 1995) and while following a lead car (Goodrich & Boer, 1997). The finding that observers can discriminate variations in the ratio $\theta/(d\theta/dt)$ while ignoring simultaneous variations in θ and $d\theta/dt$ is consistent with these proposals (Regan & Hamstra, 1993). In addition, it has been shown that observers can estimate absolute TTC using Equation 1 with a high degree of accuracy: Errors can be as small as 2–12% (Gray & Regan, 1998).

However, there are several situations where Equation 1 is not an effective source of TTC information. When the angular size of an approaching object is smaller than roughly 0.03°, observers cannot discriminate TTC on the basis of the ratio $\theta/(d\theta/dt)$ (Gray & Regan, 1998). Another problem with using Equation 1 arises when the approaching object is nonspherical and rotating, for example, a car leaving a rotary. Gray and Regan, 1999b, reported that the

estimate of TTC for a simulated rotating nonspherical object was significantly different from the estimate for a simulated spherical object with the same TTC. However, for both small targets and nonspherical rotating targets, binocular TTC information can be used to estimate TTC accurately (Gray & Regan, 1998, 1999b).

Gray and Regan (1999a) suggested that prolonged exposure to retinal image expansion may be a potential cause of accidents. They showed that adaptation to expansion causes large overestimations of TTC. Observers adapted to circular target whose size was increased with a ramping waveform for 10 min. Following this adaptation period, TTC estimates were 15–27% longer than following adaptation to a constant-sized target. Furthermore, substantial overestimations (8–16%) still occurred when estimates of TTC were based on binocular information. So, unlike the situations described above, binocular TTC information cannot be used to compensate for the inadequacy of monocular information caused by adaptation to expansion.

Gray and Regan (1999a) suggested that this adaptation effect may place driver's at risk for a high-speed rear-end collision. In particular, after a period of high-speed driving while staring straight ahead at an empty textured road, exposure to continuous retinal image expansion might cause a driver to overestimate the TTC with the lead car when overtaking. This overestimation would presumably cause driver's to initiate overtaking maneuvers at a shorter actual TTC with the lead car, leaving less margin for error if the lead car were to brake suddenly. The purpose of the study reported here was to test this prediction in a driving simulator.

General Method

Apparatus

All experiments were performed in a fixed-base driving simulator composed of two main components: the frontal two-thirds of a Nissan 240SX convertible and a wide-field-of-view (60° horizontal × 40° vertical) display of a simulated driving scene. The visual scene was rendered and updated by an Octane workstation (Silicon Graphics Inc.). It was projected onto a wall 3.5 m in front of the driver with a Barco 800G projector and was continually changed at an average rate of 15 frames/s in correspondence with the movement of the car. Unless otherwise stated, a texture pattern resembling black cracks on a gray background was mapped onto the surface of the road. The sky was blue and the surrounding ground was green, so the edges of the road were highly visible. Yellow stripes (1.5 m in length and spaced 10 m center to center) ran down the center of the road. Each lane was 5 m wide and subtended approximately 10° at a virtual distance of 20 m from the car. To aid the driver in assessing the 3-D motion of the car, short (0.5 m height) white posts were placed along the edges of the road (10 m apart). Other vehicles in the driving scene had a red body, black tires, and always followed a path down the center of the right lane. The position at which the other vehicles first appeared, and their travelling speed were varied as described below. The driving simulator provided limited kinesthetic feedback through the torque in the steering wheel and audio feedback in the form of engine noise that increased with increased car speed.

Data Analysis

Four measurements were recorded at a rate of 20 samples/s and analyzed: lateral position, distance from the start of the road, speed, and distance from other cars. The smallest change in distance or lateral position that could be detected was 0.1 m. From these records the TTC and time headway (TH) were computed.[1]

The standard deviation of lateral position while driving on the first 200 m of empty straight road (SD_{EMPTY}) was computed for each experimental trial. We defined the initiation of an overtaking maneuver as a change in lateral position toward the center of the road that was greater than SD_{EMPTY}.

Observers

Eighteen observers participated in the study. All observers were experienced drivers with a minimum of 3 years of driving experience. Participants ranged in age from 19 to 36 years with a mean age of 22.7 years. All observers except for Observer 2 (author Rob Gray) were naive to the aims of the experiment and were paid an hourly rate.

Experiment 1

Purpose

The purpose of Experiment 1 was to evaluate the effect of adaptation to expansion on overtaking performance in an unconstrained driving task.

Method

Procedure. Each experimental session began with a 10-min practice trial designed to allow observers to become comfortable with driving in the virtual environment. During this session observers drove on a roadway with several curves, and there were no other vehicles on the road. Following this 10-min period, observers performed one practice overtaking trial.

The driving scene during the overtaking portion of the experiment was as follows. Observers drove along 3,000 m of straight road at their own preferred speed. They were instructed to stay in the right lane except when overtaking other vehicles. To control the presentation of other vehicles, the roadway was divided into fifteen 200-m segments. During the first 200-m segment, there were no other vehicles on the road. Within the remaining 14 segments, there were 8 segments (chosen randomly) in which another vehicle appeared. The initial distances of the other vehicles (as measured from the beginning of the particular 200-m road segment they appeared in) ranged from 65–85 m, and their speeds ranged from 14 to 20 m/s (i.e., 32 to 45 mph). All of these vehicles traveled at a constant speed.

During overtaking maneuvers, observers were instructed to overtake the cars in the same way that they would on a real highway. It was emphasized to participants that they should pass early enough to avoid colliding with the lead car but should not to go into the left lane too early because there may be cars coming the other way (this never actually occurred in the present study). No feedback was given as to the success of their overtaking maneuver.

Each test session consisted of three conditions: (1) no-expansion baseline (2) varying expansion baseline, and (3) adaptation to constant expansion. The order of the three conditions was counterbalanced, and there were

[1] The distinction between time to collision (TTC) and time headway (TH) can be best understood if we consider a car-following situation. If the follower maintains a constant distance behind the lead vehicle, the TTC (i.e., the time until the front bumper of the follower's car contacts the rear bumper of the lead car) is infinite. On the other hand, the TH, defined as the time until the front bumper of the follower's car reaches the location on the roadway currently occupied by the rear bumper of the lead vehicle (Lee, 1976), is finite and will depend on the follower's speed. In general, TH appears to be a more important control variable than TTC in driving situations involving a lead vehicle (Goodrich & Boer, 1997; Lee, 1976; Van Winsum & Heino, 1996).

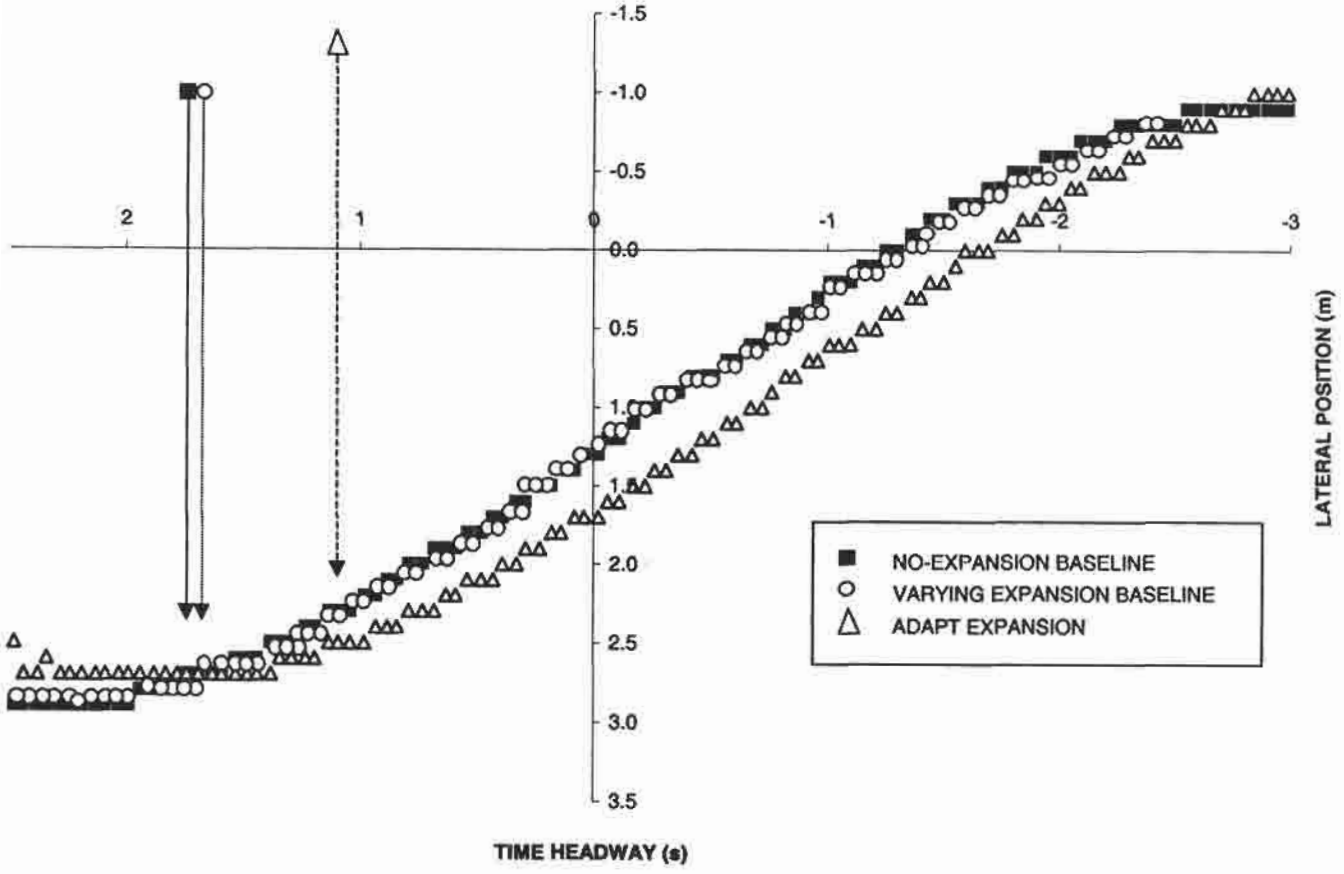


Figure 1. Lateral car position plotted as function of the time headway (TH) with the lead vehicle for Observer 1. Negative lateral positions represent driving in the left lane and positive positions represent driving in the right lane. A negative time headway indicates that the front bumper of observer's simulated car was further down the road than the slowly moving vehicle's rear bumper. Solid squares are for the no-flow condition, open circles are for the varying-flow-baseline condition, and open triangles are for the adapt-expansion condition. The speed and initial distance of the lead car were identical for all three conditions. The onset of the overtaking maneuvers in the three conditions is shown with black arrows.

10-min breaks between each condition to minimize any carryover of adaptation effects. These conditions were as follows.

No-expansion baseline condition. Observers sat in the car and stared straight ahead at a static view of the driving scene for 5 min. This baseline condition is analogous to the baseline condition we used in a psychophysical experiment examining the effects of adaptation on TTC judgments (Gray & Regan, 1999a). During the 5-min period, pressing down on the accelerator or turning the steering wheel did not alter the visual display. A brief auditory tone signaled the end of the 5-min period after which observers immediately completed one overtaking session. Observers were instructed to begin driving forward immediately after they heard the tone.

Varying-expansion baseline condition. This condition was identical to Condition 1 except for the following. Instead of remaining stationary for the initial 5-min period, observers drove through a road with several curves at any speed they felt comfortable. There were on average 12 curves per 4,000 m of driving so that the driver was essentially continuously negotiating curves for 5 min. In this condition, we predicted that no motion-in-depth (MID) aftereffect would be produced because the focus of expansion of the visual flow field is continuously changing as the observer steers the car around the curves. Psychophysical studies have shown that MID aftereffects produced by adaptation to a radial flow field only occur for objects very close (within roughly 0.5°) to the prior location of the focus of expansion (Regan & Beverley, 1979).

Adaptation to constant expansion condition. This condition was identical to Conditions 1 and 2 except for the following. During the initial 5 min period observers were instructed to drive straight ahead on a straight empty road at a speed which was comfortable to them. They were further instructed to keep looking at the road in front of the car as if they were taking a long drive on a deserted highway. No fixation point was used.[2] A small lateral drift toward the inside lane was present in all conditions so that drivers were required to actively steer even when driving straight ahead.

Results

Figure 1 plots the lateral position of the car as function of the time headway (TH) with the lead vehicle for Observer 1. These

[2] As one reviewer suggests, although we did not use an explicit fixation point in our experiments, the relatively small number of objects in our simulated environment may have reduced the frequency of saccades relative to a real environment with road signs, landmarks, etc. Whether the adaptation effects reported here can be reduced by encouraging more frequent eye movements during the adaptation period is an important theoretical and practical question that should be addressed in future research.

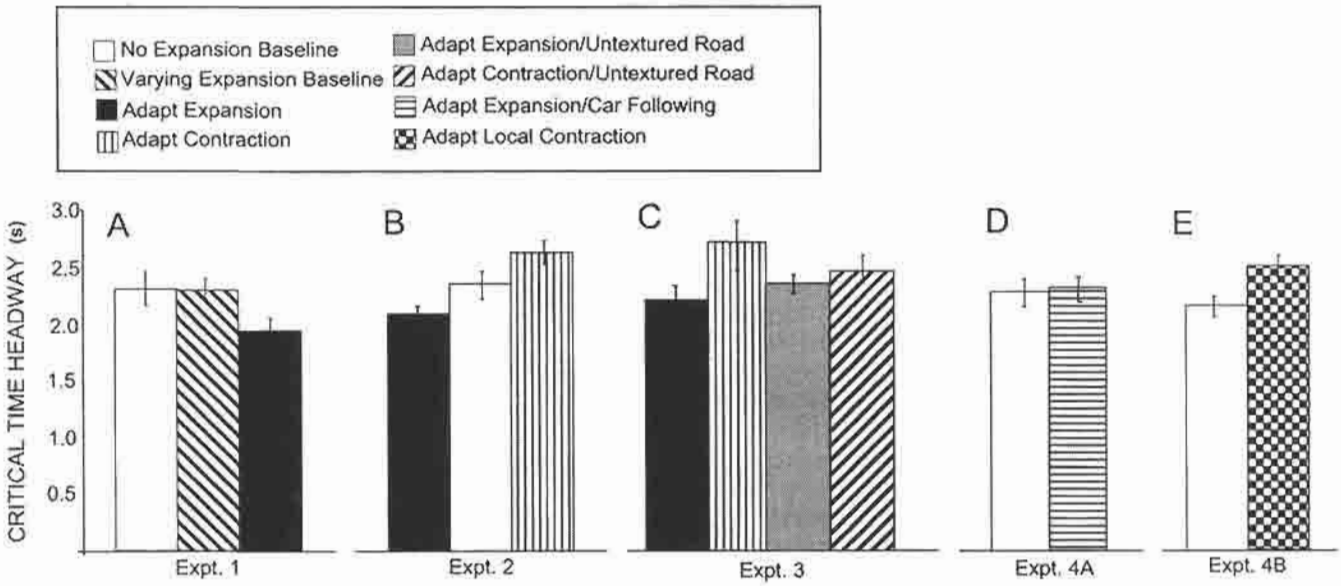


Figure 2. Mean critical time headway values for four experiments. See legend and text for details. Error bars represent ±1 *SE*. Expt. = experiment.

data are for one particular pass during the overtaking session. The speed and initial distance of the lead car were identical for all three conditions. The onset of the overtaking maneuvers in the three conditions is shown with black arrows. The onset of the overtaking maneuver (the critical time headway) occurred at a TH value of 1.74 s for no-flow baseline (solid squares), 1.61 s for the varying-flow baseline (open circles), and 1.13 s for the adapt-expansion condition (open triangles).

Similar results were obtained for 7 other observers. The mean critical TH values averaged across the 8 maneuvers for all 8 observers are shown in Figure 2A. A repeated-measures analysis of variance (ANOVA) comparing the mean critical TH values revealed a significant effect of condition, $F(2, 14) = 41.73$, $p < 0.001$. We made two comparisons of treatment means (Keppel, 1991). The mean critical TH for the two baseline conditions was not significantly different, $F(1, 7) = 0.05$, $p > 0.5$, and the mean critical TH for the adapt-expansion condition was significantly lower than the combined mean for the two baseline conditions, $F(1, 7) = 59.90$, $p < 0.001$. The difference between the combined mean of the two baseline conditions and the mean for the adapt-expansion condition was 345 ms.

We also compared the three conditions using the speed at the onset of the overtaking maneuver as a dependent measure.[3] Mean speeds for the three conditions are shown in Figure 3. A repeated-measures ANOVA revealed a significant effect of condition, $F(2, 14) = 3.80$, $p < 0.05$, on the speed data. Comparisons between treatment means revealed no significant difference between the mean speeds in the two baseline conditions, $F(1, 7) = 0.90$, $p > 0.5$, and that the mean speed in the adapt-to-expansion condition was significantly higher than the combined means for the two baseline conditions, $F(1, 70) = 5.60$, $p < 0.05$. The finding that observers drive at a higher speed following adaptation to expansion provides further evidence that driving on a straight empty road produces a substantial adaptation effect. The effect of adaptation on driving speed is discussed below.

Finally, we evaluated how well observers followed the instruction to "drive straight ahead down the center of the right lane" during the adapt-expansion condition. If observers did not maintain a roughly straight course during the adaptation condition, the location of the focus of expansion would change during the adaptation period. Our observers maintained their lane position very precisely. The mean lane position ranged from 1.98 m to 2.5 m (measured from the center), and the standard deviation of lateral position ranged from 0.13 m to 0.29 m.

Discussion

Adaptation to retinal image expansion has a dramatic effect on overtaking maneuvers. Following simulated driving on a straight empty road for 5 min, drivers' initiated overtaking 218–510 ms later than comparable maneuvers made following 5 min of remaining stationary or 5 min of curve driving. There are two driving control strategies that could explain these temporal shifts in overtaking: a constant TH strategy and a constant perceived distance strategy. We now consider these two strategies.

If drivers initiate overtaking at a constant TH, the observed changes in overtaking behavior could be explained in terms of an overestimation of the TH with the lead car produced by adaptation to expansion. Regan and Beverley (1979) have shown that detection thresholds for MID were elevated after adapting to a radially expanding flow pattern for which the divergence of velocity (div *V*) was large in the immediate vicinity of the focus of expansion. Their observers adapted to a radial flow pattern for 10 min. As shown in Figure 4, detection thresholds for oscillations in the size of a small (0.5°) square test target were substantially elevated for objects located at the point in the visual field previously occupied

[3] Similar effects of driving speed were obtained when we used the average speed for the 500 m prior to the initiation of overtaking.

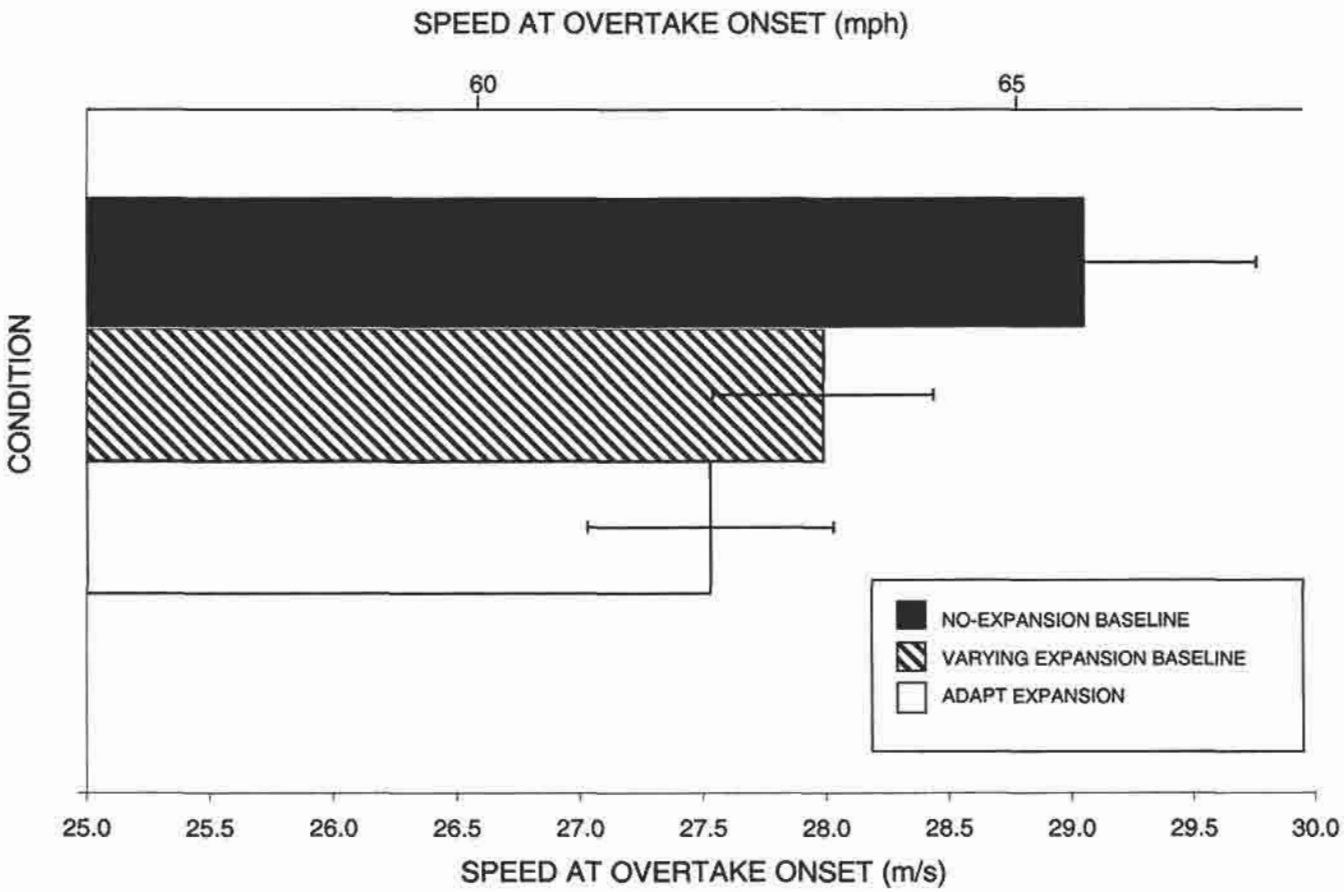


Figure 3. Mean driving speed at the onset of overtaking averaged across the 8 observers who participated in Experiment 1. Solid bars are for the no-flow-baseline condition, open bars are for the varying-flow-baseline condition, and hatched bars are for the adapt-to-expansion condition. Error bars represent ±1 *SE*.

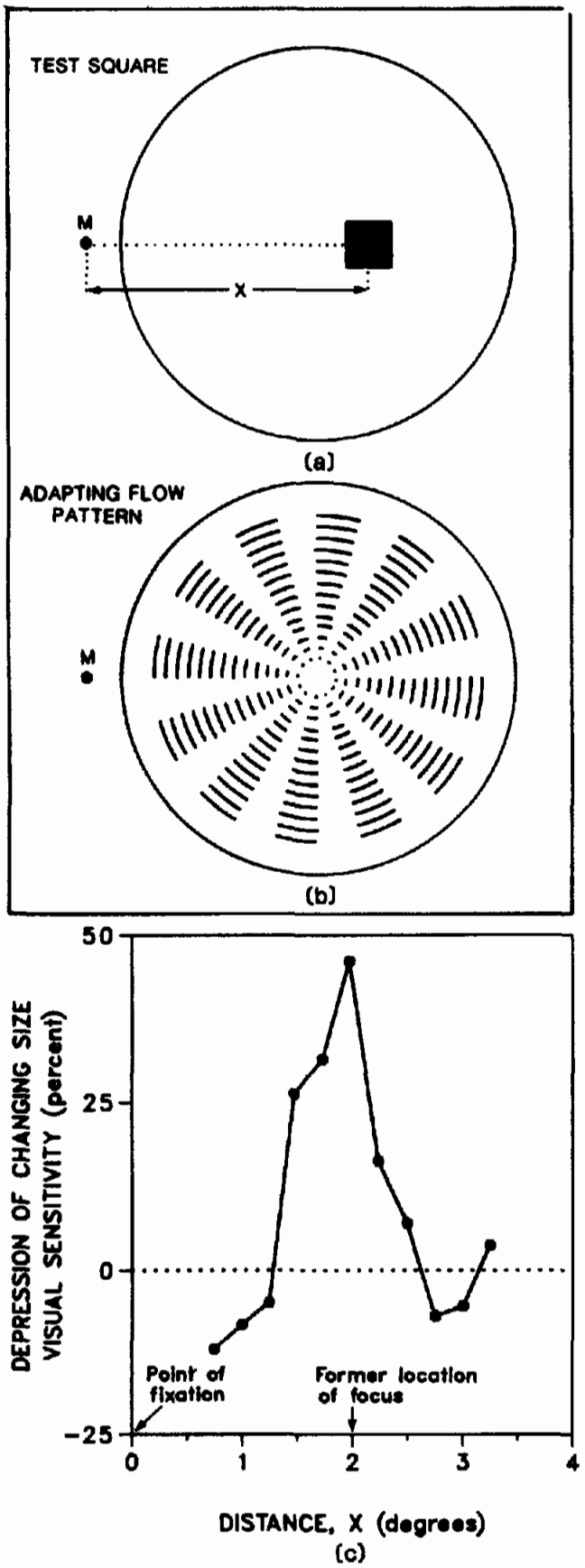
by the focus of expansion of the flow pattern (i.e., at 2°). Threshold elevations fell off sharply for objects located away from this location. No such effect was observed for a test target of constant size that oscillated in location.

The threshold elevation shown in Figure 4 is of similar size to that produced by adapting to changes in the size of a small square (Regan & Beverley, 1978), a kind of adaptation that we have shown also causes observers to overestimate TTC (Gray & Regan, 1999a). On this basis we predicted that adapting to a radially expanding flow pattern would cause observers to overestimate the TTC of objects located at the prior location of the focus of expansion.

In the present experiment, the focus of expansion of the adapting pattern (i.e., the outward flow of the road texture, lane-markers, etc.) was located at approximately the same position in the visual field where the lead vehicle appeared during overtaking maneuvers. If a driver's control strategy was to initiate an overtaking maneuver at a constant TH, the overestimation of TTC would lead to a temporal shift in the pattern of overtaking similar to that shown in Figure 1. In Experiment 1, the mean percentage change in the critical TH was 17% ($SE = 3$). This value is similar to the mean percentage change in estimated TTC (20%, $SE = 2$) following adaptation a single expanding object (Gray & Regan, 1999a).

Temporal shifts in overtaking patterns would also be predicted by a constant distance control strategy. In Experiment 1, we found that observers drove significantly faster in the adaptation condition than in either of the baseline conditions (see Figure 3). In a series of studies, Denton (1976, 1977, 1980) has shown that prolonged exposure to simulated forward motion produces underestimations of perceived speed. Following a 250-s adaptation period, observers underestimated their traveling speed by amounts varying from 17–50%. In an interesting field study, Mathews (1978) reported that drivers traveling northbound on a section of road (connected to an expressway with a speed limit of 96 mph) drove 8% faster than drivers traveling southbound on the same stretch of road (connected to an urban road with a speed limit of 64 mph). The increase in driving speed (7.5% on average) following adaptation to expansion we reported in Experiment 1 is consistent with these findings; because drivers feel as though they are going slower following adaptation-to-expansion, they drive at a faster actual speed.

If drivers used a control strategy of initiating overtaking maneuvers at a constant distance from the lead car instead of using a constant TH, this increase in driving speed following adaptation would cause a similar temporal shift in the overtaking pattern. In other words, a driver's critical distance for initiation of overtaking



would be associated with a shorter TH when driving speed was increased. In Experiment 2 we attempted to dissociate these two strategies by holding driving speed constant across conditions.

Experiment 2

Purpose and Rationale

To distinguish between a constant TH strategy and a constant distance strategy, we removed the driver's ability to vary the speed of the car in Experiment 2. If the temporal shifts observed in Experiment 1 were solely due to the increase in driving speed following adaptation-to-expansion, we would expect no temporal shifts to occur when driving speed is held constant between the baseline and adaptation conditions.

In Experiment 2 we also tested a new adaptation condition: adaptation-to-contraction produced by an extended period of driving backward.

Method

The procedure was as described for Experiment 1 except for the following. The test session was composed of three conditions: (1) no-expansion baseline, (2) adaptation to expansion, and (3) adaptation to contraction. We did not use the varying-expansion baseline condition in Experiment 2 because in Experiment 1 it did not produce significantly different results from the no-expansion baseline. For these three conditions and during all the overtaking maneuvers, the car traveled at a constant speed of 24 m/s (50 mph). Thus, unlike Experiment 1, in Experiment 2 the driver only controlled the lateral position of the car. In Condition 3 the simulated car traveled backward (i.e., away from the screen) during the initial 5-min period and switched to travelling forward for the overtaking session. Because speed was held constant, the transition between backward and forward driving was the same for all observers. The order of the 3 conditions was counterbalanced. There were 10-min break periods between each of the conditions to prevent any carryover of adaptation effects.

Results

Figure 2B shows the mean critical TH, averaged across 9 observers, for the three conditions. Similar to Experiment 1, the mean critical TH value for adapt-expansion condition was 252 ms shorter than in the baseline condition. Conversely, the mean critical TH for the adaptation-to-contraction condition was longer (by approximately 270 ms) than in the baseline condition.

A repeated-measures ANOVA revealed a significant effect of condition, $F(2, 16) = 5.40$, $p < 0.025$. A comparison of treatment means revealed a significant difference between the critical TH in the adapt-expansion condition and the critical TH in the adapt-contraction condition, $F(2, 16) = 54.60$, $p < 0.001$.

Figure 4. (a) Sensitivity to size oscillations of a 0.5° test square located a variable distance (X) from the point of fixation (M) were measured before and after adaptation. (b) Observers adapted to a radially expanding flow pattern for 10 min. (c) Depression of changing-size sensitivity as a function of distance X. Threshold elevations only occurred for points very close to the former location of the flow pattern's focus. From "Visually Guided Locomotion: Psychophysical Evidence for a Neural Mechanism Sensitive to Flow Patterns," by D. Regan and K. I. Beverley, 1979, *Science* (http://www.sciencemag.org), *205*, pp. 311–313. Copyright 1979 by the American Association for the Advancement of Science. Reprinted with permission.

Discussion

In Experiment 2, significant adaptation effects occurred even though the driving speed was identical in all conditions. This finding indicates that our observers did not use a constant distance strategy for the initiation of overtaking maneuvers in Experiment 2 and that changes in perceived speed following adaptation to expansion are not the only cause of the observed changes in overtaking patterns. With speed held constant, a constant distance strategy should produce no difference in the timing of overtaking maneuvers for the three conditions used in Experiment 2, assuming that the adaptation conditions do not differentially effect judgments of perceived distance. However, these findings do not rule out the possibility that drivers may use different control strategies depending on the situation (e.g., their driving speed). In a companion study to the one reported here (Gray & Regan, 1999d), we examine the relative contribution of time headway, perceived distance, and perceived speed to the onset of overtaking maneuvers in more detail.

Why did drivers initiate overtaking significantly earlier following adaptation-to-contraction? This effect can also be explained by our misestimation of time headway model because adaptation to a continuously contracting visual scene should cause drivers underestimate TH.

Experiment 3

Purpose and Rationale

The relative contribution of central and peripheral visual information to the perception of self-motion has recently garnered a great deal of attention (e.g., Howard & Heckman, 1989; Telford, Spratley, & Frost, 1992; Warren & Kurtz, 1992). The hypothesis that, in general, peripheral vision dominates the perception and control of self-motion (Brandt, Dichgans, & Koenig, 1973) conflicts with recent findings that perceived self-motion can be driven by central vision under certain conditions, namely, when the central field is perceived as the background of the display (Howard & Heckman, 1989). The purpose of Experiment 3 was to examine the relative contribution of central and peripheral changing-size information to the effects of adaptation on overtaking. We chose to reduce the central changing-size information (i.e., around the location of the focus of expansion) by removing the texture from the surface of the road. All other changing-size information including the expansion of the road stripes, and road-side markers outside the central visual field was still present.

Method

The method was as described for Experiment 2 except for the following. Observers participated in two separate test sessions: Textured road and Untextured road. The textured road was as described above. The untextured road was solid gray. The order of these two sessions was counterbalanced across observers. To keep experimental runs reasonably short, while still preventing carry-over of adaptation effects across conditions, we only compared the adapt-expansion and adapt-contraction conditions.

Results

The mean critical TH values, averaged across 8 observers, are shown in Figure 2C. Results for the textured-road test (black and vertical-striped bars) were similar to the results of Experiment 2: The critical TH in the adapt-expansion condition was significantly shorter than in adapt-contraction condition, $t(10) = 8.29$, $p < 0.001$. The difference in critical TTH values was roughly 495 ms. For the untextured-road test (gray and diagonally striped bars), the difference in TH values for the two conditions (113 ms), though significant, $t(10) = 2.24$, $p < 0.05$, was considerably smaller than for the textured-road test.

A two-factor repeated-measures ANOVA revealed a significant effect of adaptation condition, $F(1, 10) = 26.63$, $p < 0.001$, and a significant Condition × Road-Type interaction, $F(1, 10) = 11.09$, $p < 0.01$. Figure 2C shows that the significant interaction occurred because the effect of adapt-condition was larger for the textured-road than for the untextured-road test.

Discussion

The difference between the critical TH for the adaptation-to-expansion and adaptation-to-contraction conditions was considerably larger (by 382 ms) for a textured road than an untextured road. The peripheral changing-size information including the poles on the edge of the road, the road stripes, and the grass texture were identical for these two conditions. We propose that changes in overtaking maneuvers following adaptation are primarily caused by the adaptation of local, central visual field, changing-size detectors that signal motion-in-depth for objects near the focus of expansion. However, although much smaller, the adaptation effect produced with the untextured road was still significant. This suggests that information in the peripheral flow field does contribute to the adaptation effects. In Experiment 4, we further examined the relative contributions of central and peripheral changing-size information.

Beverley and Regan (1982) reported similar effects in an extension of their study examining the effects of adaptation to flow patterns on MID sensitivity. As described above, following adaptation to a radial flow pattern, MID thresholds are elevated for targets located near the point space previously occupied by the focus of expansion (Figure 5—top graph). However, occluding the center of the flow pattern dramatically alters this effect. As shown in Figure 5 (bottom graph), a 2° hole in the adapting flow pattern effectively eliminates the selective elevation of MID thresholds for objects located near the prior location of the focus of expansion. In the present study, the removal of the road texture created a hole at the center of the flow pattern.

Experiment 4

Purpose and Rationale

The results of Experiment 3 suggest that the effects of adaptation on overtaking maneuvers are primarily caused by selective adaptation of mechanisms that signal motion-in-depth near the location of the focus of expansion. If this adaptation effect is due to local adaptation of changing-size detectors, we predict (a) there should be no adaptation effect with a textured road when objects near the focus of expansion remain constant in size, and (b) there should be an adaptation effect on an untextured road when a small adaptation stimulus (e.g., a single changing-size target) is located

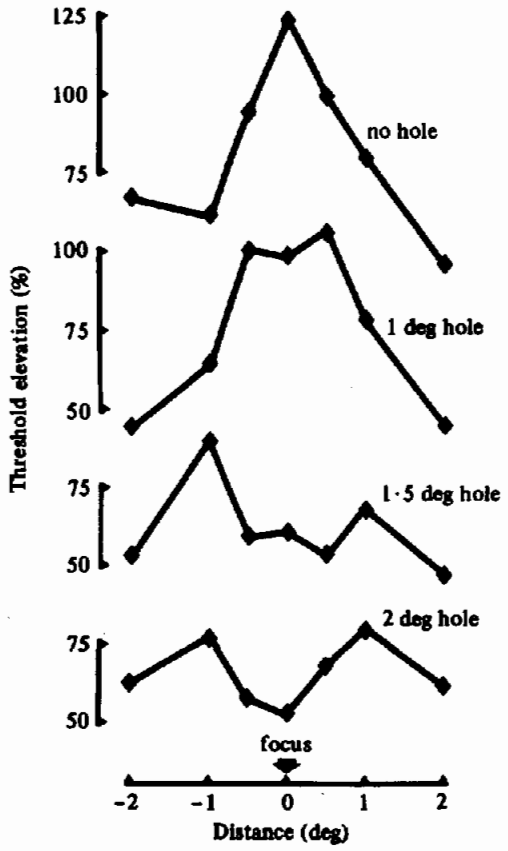


Figure 5. Effect of occluding the center of the radially expanding adaptation pattern on motion-in-depth sensitivity. Ordinates plot threshold elevations for changing-size test square. Abcissae plot the distances between the former location of the focus of expansion of the flow pattern and the center of the test square. From "Adaptation to incomplete flow patterns: No evidence for 'filling-in' the perception of flow patterns," by K. I. Beverley and D. Regan, 1982, *Perception, 11*, p. 277. Copyright 1982 by Pion Limited, London. Reprinted with permission.

near the focus of expansion. The purpose of Experiments 4A and 4B was to test these two predictions.

Experiment 4A: Textured Road With Car Following

Method. In order to reduce the changing size information near the focus of expansion, we introduced a car-following task to the adaption period. If a driver maintains a constant distance behind a lead car, there will be no stimulation of looming detectors close to the focus of expansion. On the other hand, the radial flow in peripheral vision produced by the road markers, etc., will be identical to the adaptation-to-constant-expansion condition used in Experiments 1–3.

In Experiment 4A we compared this car-following. condition with the no-expansion baseline used in Experiments 1 and 2. During the car-following condition, observers were instructed to speed up until they reached what they felt was a safe distance behind the lead car and then attempt to maintain this separation. The lead car's initial distance was 55 m, and it traveled at a constant speed of 22 m/s (50 mph). At the end of the 5-min period, the lead car pulled off the side of the road and the overtaking session, as described for Experiment 1, began. All observers completed two no-expansion-baseline sessions and two car-following sessions. The order of these sessions was counterbalanced across observers, and there were 10-min breaks between the sessions.

Results. Figure 2D shows the mean critical TH for 8 observers. Addition of the car-following task during the adaptation phase (horizontally striped bars) effectively eliminated any changes in overtaking maneuvers. The mean critical TH in the baseline condition was not significantly different from the mean critical TH in the car-following condition, $t(14) = 0.06$, $p > 0.5$.

Experiment 4B: Untextured Road With a Local Adaptation Stimulus

Method. The procedure and stimuli were identical to Experiment 1 except for the following. Drivers completed two no-expansion baseline and two adapt-local-contraction conditions with the order counterbalanced. In these sessions the observer's car traveled forward at a constant speed of 22 m/s. A constant driving speed was necessary in Experiment 4B to allow for control over the position and rate of contraction of the adaptation stimulus. The local adaptation stimulus was a red square that was centered at the focus of expansion. The initial side length of the adapting square was 4.7°. The square continuously decreased in size at a rate of 2.1°/s. Once the side length reached 1.6°, the square disappeared for 70 ms, reappeared at its original size, contracted in size, and so on. The flyback was never visible to the observer. This ramped contraction can also be thought of as a single object that first appears 30 m down the road from the observer's car and moves away from the observer at a rate 35 m/s until it is 80 m from the observer's car. When the observer traveled over road segments in which another car was not present, the adaptation stimulus was presented again.

Results. Figure 2E shows the mean critical TH for 8 observers. Despite the lack of road texture in Experiment 4B, the mean critical TH in the adapt-local-contraction condition (checkered bar) was significantly greater than the mean critical TH in the baseline condition, $t(14) = 2.50$, $p < 0.025$.

Discussion

In Experiment 4A, introducing a car-following task to the adaptation period effectively eliminated overtaking adaptation effects on a textured road. In Experiment 4B, we found a significant adaptation effect on an untextured road when observers adapted to a single contracting target centered on the focus of expansion. These two observations provide further evidence that changes in overtaking maneuvers following adaptation are primarily determined by the output of changing-size filters with receptive fields located near the focus of retinal image expansion.

General Discussion

A Consequence of Motion Adaptation for Visually Guided Motor Action

Despite the considerable research effort that has been devoted to visual motion aftereffects (e.g., see Wade, 1994, Appendix 1, for a list of over 300 references), we have only been able to find a small number of studies that have examined the effects of motion adaptation on visually guided motor action. Miller and Weider (1975) investigated the effects of adaptation on a paper-and-pencil tracking task. Observers were required to keep a pencil in the center of a track drawn on a paper tape that moved at a speed that the observer could control with a foot pedal. Following exposure to a constant high-speed tracking task, observers traveled faster

and made more errors than following the same duration of self-paced tracking. Denton (1976) examined the effects of adaptation to forward motion on a simulated driving task. Following 3 min of exposure to a constant simulated forward velocity of 70 mph, speed was dropped to 30 mph, and the observer's task was to adjust a hand throttle to keep speed constant at this value. The actual velocity needed to keep the same subjective speed decreased with time, consistent with a underestimation of speed following adaptation. Adaptation effects following running on a treadmill have also been reported (Anstis, 1995).

Our findings suggest that adaptation to MID might have a marked effect on a common visually guided motor action. Following prolonged exposure to retinal image expansion produced by simulated driving on a straight empty road for 5 min, our observers initiated overtaking of a slowly moving vehicle substantially later (by 225–500 ms) than comparable maneuvers made either following adaptation to a static visual scene or following 5 min of curve driving. Adaptation to continuous contraction produced by a 5-min period of driving backward had the opposite effect on overtaking: Observers initiated overtaking significantly sooner (by 100–450 ms). Therefore, the well-documented changes in visual perception following adaptation to motion [e.g., perceived speed (Denton, 1977; Pantle & Sekuler, 1968) and perceived direction (Beverley & Regan, 1973; Levinson & Sekuler, 1976)] can also be accompanied by changes in a visually guided motor action.

Central Versus Peripheral Changing-Size Information

The effects of adaptation to MID on overtaking maneuvers appear to depend primarily on changing-size detectors with receptive fields near the focus of expansion. Removing the texture from the surface of the simulated road dramatically reduces the changing-size information near the focus of expansion, though it has no effect on expansion information in the peripheral visual field. A similar reduction in changing-size information near the focus of expansion occurs when a driver maintains a roughly constant distance behind a lead vehicle. In both these situations, adaptation effects were significantly reduced. These findings suggest that drivers use predominately information in the central visual field when initiating an overtaking maneuver. Peripheral changing-size mechanisms contribute only minimally to these effects.

Implications for Motion in Depth and TTC Processing

In a series of articles, we have developed a model of the visual processing of retinal image expansion and the consequent generation of MID perception (reviewed in Regan, 1991, and Regan & Gray, 1999). Figure 6 shows a recent version that describes the early processing of monocularly available motion-in-depth information for textured objects (Gray & Regan, 1999c). The circle at the upper left of Figure 6 indicates the boundary of a single texture element on the surface of an object. The object subtends an angle θ_V vertically. Two pairs of local motion (LM) filters that are tuned to horizontal and vertical motion, respectively, feed two relative motion (RM) filters that encode the rates of expansion of the texture element's horizontal (S_H) and vertical (S_V) diameters, respectively. The output of an RM filter is proportional to a constant k, which we assume to be inversely proportional to the angular separation of the two LM filters that feed a particular RM filter. This assumption makes the output of each RM filter inversely proportional to TTC. Figure 6 also illustrates the processing of changes in the angular size of the entire object (RM filter fed by signals a and f) and changes in the separation between adjacent texture elements (RM filter fed by signals b and e). Finally, Figure 6 shows that the final MID signal is generated from a weighted average of the signals from all RM filters. From TTC estimation results (Gray & Regan, 1999c), we proposed that the rate of expansion information provided by the texture elements is weighted less heavily than the information provided by the object size when the size of the elements is below a critical size (roughly 2–4 arc min).

We now discuss how this model relates to the findings of the present study. In Experiment 3 we found that the adaptation effect was dramatically reduced when the texture was removed from the surface of the road. This finding provides further evidence that the rate of expansion of the texture on the surface of an object contributes strongly to the sensation of MID and consequent estimate of TTC (Beverley & Regan, 1983; Gray & Regan, 1999c; Vincent & Regan, 1997).

Although removing road texture much reduced the effect of adaptation, the effect with an untextured road, though small, was still significant. However, in Experiment 4A we found that there was no significant adaptation effect when a car-following task was added to the adaptation phase. Because both manipulations effectively removed changing size information near the location of the focus of expansion, why were adaptation effects different for the two conditions? We propose that this can be explained in terms of the relative weighting of expansion information in the Figure 6 model. When driving on an untextured road, the texture elements are below the critical size of 2–4 arc min; therefore, the expansion information provided by the edges of the road will be weighted more heavily. On the other hand, when a driver is following another vehicle, the angular size of the lead vehicle is well above the critical size, and its lack of expansion will be given a substantial weighting in the averaging stage shown in Figure 6.

Consistent with previous studies (e.g., Goodrich & Boer, 1997; Lee, 1976), the results reported here indicate that time headway is an important perceptual variable for driving. Given that angular size of the lead vehicle cannot be used to estimate TH (see Footnote 1), it is interesting to consider what retinal image information a driver could use to estimate TH. A potential source of TH information is the rate of expansion of the texture elements on the surface of road. One alternative information source could be the rate of separation of any two features on the road (e.g., opposite edges of the road). The model shown in Figure 6 indicates that the rate of increase of texture element size and rate of increase of element separation both feed into the final MID signal (and the subsequent estimate of TTC) for an approaching textured object. Therefore, our MID model could generate an estimate of TH based on either of the retinal images variables described above. From previous findings on TTC (Gray & Regan, 1999c), we would predict that both sources of TH information may be used during driving with the relative weighting of the two information sources depending on the size of roadway features (e.g., whether texture elements on the surface of the road are larger than the critical size of 2–4 arc min).

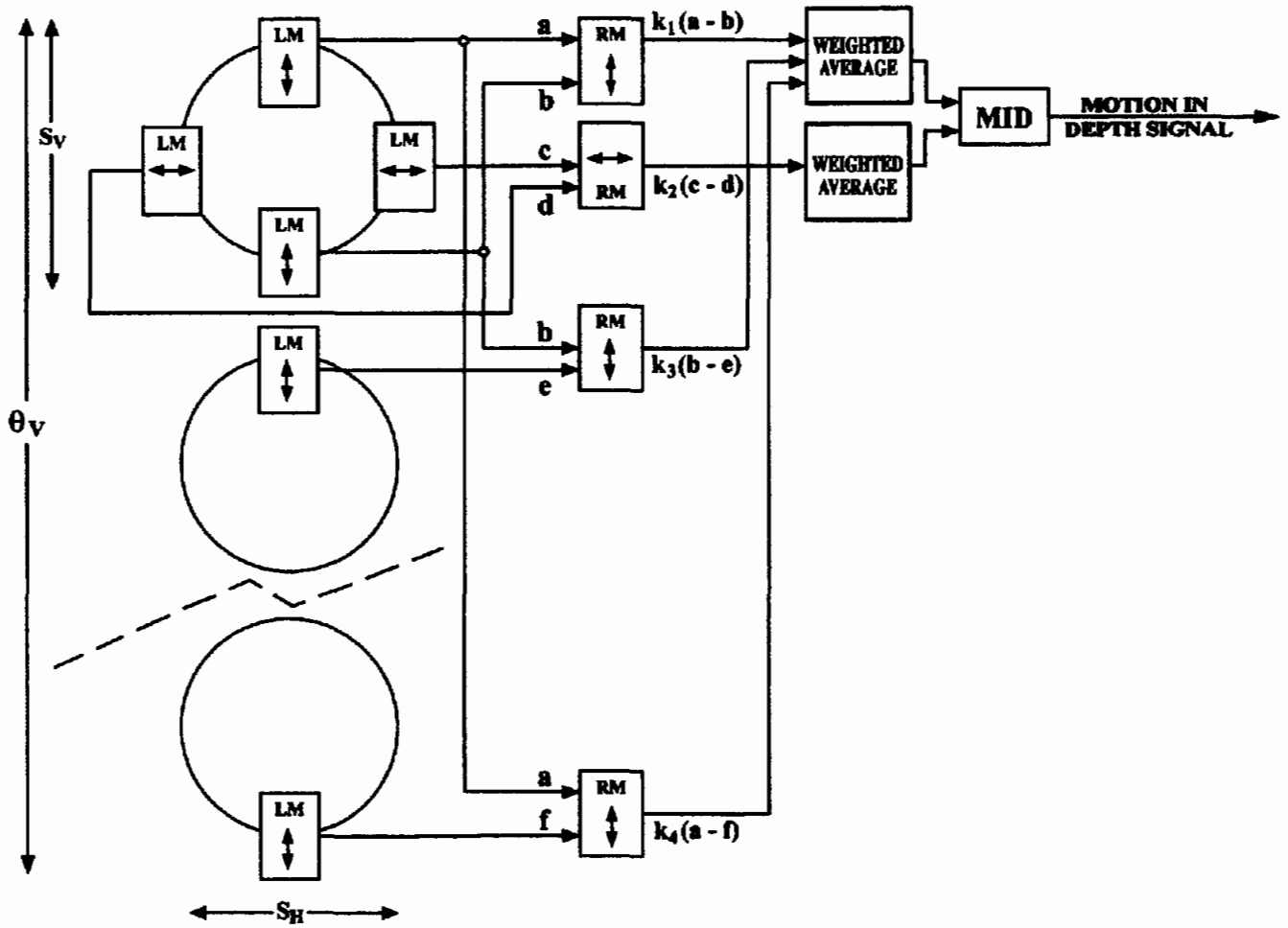


Figure 6. Model of the processing of motion in depth and TTC for a textured object. The object's retinal image subtends θ_V vertically and θ_H horizontally. For clarity, only the vertical dimension is shown. The texture elements (circles on left side of the figure) subtend S_V vertically × S_H horizontally. The top and bottom texture elements demarcate the upper and lower boundaries of the object's retinal image, and the jagged dashed line indicates that several texture elements may lie between the bottom and middle texture elements. LMs represent filters sensitive to local motion along the directions arrowed. Their outputs (a–f) are proportional to the speed of motion, and their sign represents the direction of motion. RM represents relative motion filters whose outputs signal the rate of change and direction (expansion vs. contraction) of angular subtense along a given retinal meridian. Outputs from RM filters sensitive to change in texture element angular size [e.g., k_1(a–b)], change in the angular separation between texture elements [e.g., k_3(b–e)], and change in object angular size [e.g., k_4(a–f)] are weighted and averaged to process the final motion-in-depth (MID) signal. From "Motion in depth: Adequate and inadequate simulation," by R. Gray and D. Regan, 1999, *Perception & Psychophysics, 61,* p. 243. Copyright 1999 by Psychonomic Society, Inc. Reprinted with permission.

Possible neural correlates of this model of MID processing have been identified (see Rind & Simmons, 1999, for a recent review); however, the functional model described here may not necessarily correspond on a one-on-one basis with the physical structure of the human brain (see Regan, 1999, for a discussion of this point).

Implications for Driving

We recently proposed (Gray & Regan, 1999a) that the lengthening of perceived TTC produced by adaptation to expansion may be a potential cause of traffic accidents under certain conditions. Our previous findings suggested that, after a period of high-speed driving while looking straight ahead at an empty road, a driver might overestimate the TTC and thus be at risk of clipping the rear corner of the lead vehicle while overtaking. The findings of the present simulator study are consistent with this prediction. Observers initiated overtaking substantially later following adaptation-to-expansion as would be expected if TTC were overestimated.

We have been able to find only one previous study that has examined the effects of prolonged driving on overtaking. Brown, Tickner, and Simmonds (1970) examined the effect of prolonged

driving on overtaking maneuvers in a natural setting. The main purpose of their study was to investigate the effect fatigue on driving. Observers drove for 4 × 3-hr sessions on public roads during which their driving performance was evaluated by an experimenter who rode in the passenger seat. The main finding was that risky overtaking maneuvers (as judged by the experimenter) occurred more frequently in the 4th session than in the 1st session. At first sight this qualitative finding is consistent with the results of Experiment 1. However, it is difficult to assess the role of adaptation to visual motion in Brown et al.'s (1970) experiments.

Although in no case did our drivers actually collide with the lead car in the present study, the observed changes in overtaking behavior substantially reduce the margin for error and place the driver at higher risk for a rear-end collision. In Experiment 1, in which we simulated unconstrained natural driving, 5 of the 8 observers initiated overtaking at a time headway of less than 1 s for at least one overtaking maneuver. On one occasion, a driver initiated overtaking at a TH of only 625 ms! This could lead to collision if the lead vehicle were to slow unexpectedly (e.g., due to a flat tire). Relevant numbers here are that a driver travelling at a speed of 30 m/s (68 mph) needs to initiate hard-braking at a TH of at least 4.0 s in order to avoid collision with a stationary object (Lee, 1976). Clearly, if the temporal gap between a driver and the lead vehicle is less than 1.0 s, he or she could not avoid a high-speed rear-end collision in this situation.

A more serious implication for driving may be the change in a driver's overtaking strategy in response to the effects of adaptation to expansion. Our observers often compensated for initiating overtaking at a small TH by sharing lanes with the lead car while overtaking and passing, that is, part of the observer's car always remained in the same lane as the lead vehicle. In some cases, the lateral separation between the observer's car and the lead car was less than 0.5 m when the two cars were the same distance down the road. Similar lane-sharing strategies during overtaking have been observed during real driving on public roads (Wilson & Best, 1982). Clarke, Ward, and Jones (1998) recently reported that the most common type of injury-causing overtaking accident occurs when, unexpectedly to the overtaking driver, the lead vehicle attempts to make a turn across the oncoming traffic lane, that is, a left-turn in North America. Because lane sharing reduces the spatial separation between the overtaking and lead vehicles, this strategy would leave less time for the overtaking driver to react to an unexpected turn by the lead vehicle.

Another important point to consider for highway driving is that removing the changes in driving speed following adaptation to expansion does not eliminate risky overtaking maneuvers. In Experiment 2, significant temporal shifts in overtaking patterns were found even though speed was held constant. It has previously been suggested that motion adaptation may be a potential cause of traffic accidents. Denton (1976, 1980) proposed that the underestimation of perceived speed following adaptation might cause drivers to enter roundabouts at unsafe speeds. Denton further reported that by placing white stripes across the roadway, it was possible to create a speed illusion that counteracted the adaptation effect and reduced the actual driving speed. This strategy appears to reduce the number of accidents (Denton, 1980) and is now commonly used on roundabouts and off-ramps. However, our findings suggest that it does not completely eliminate all potentially dangerous effects of adaptation to expansion.

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