Perceptual Processes Used by Drivers During Overtaking in a Driving Simulator

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This study investigated the control strategies and decision making of drivers who were executing overtaking maneuvers in a fixed-base driving simulator. It was found that drivers were frequently inaccurate in deciding whether it was safe to overtake in front of an oncoming vehicle. One source of error in this situation was the control strategy adopted by the driver; in several instances our drivers initiated an overtaking maneuver when the oncoming car’s distance was above a critical value, even though there was not sufficient time to complete a safe maneuver. Adaptation to closing speed (produced by driving on a straight open road) also had large effects on overtaking behavior. For all participants, closing speed adaptation resulted in decisions that were delayed, of higher risk, and more variable. Actual or potential applications of this research include improved training for younger drivers and the development of in-car interfaces that reduce closing speed adaptation.

INTRODUCTION

On U.S. roads, 41,821 individuals were killed and 3.2 million injured during the year 2000 (National Highway Traffic Safety Administration [NHTSA], 2000). Accident analyses implicate errors in perception and decision making as the probable cause of the majority of these accidents (Groeger, 2000). One of the more dangerous judgments a driver must make is whether there is sufficient time to complete a driving maneuver before colliding with an oncoming car – for example, in overtaking or in executing a left turn at an intersection. In the study reported here, we investigated visual-motor control and decision making during overtaking maneuvers.

Perception and Decision Making During Overtaking

Accident analyses indicate that overtaking a more slowly moving vehicle can be one of the more dangerous situations a driver faces. In the United States, overtaking accidents account for 2.1% of all fatal crashes and 1.1% of injury crashes (NHTSA, 2000). Although at first glance these numbers may seem small, it is important to note that overtaking maneuvers are performed relatively infrequently during normal driving. The situation is even worse in the United Kingdom, where two-lane rural roads make up a larger proportion of the roadway system. Jeffcoat, Skelton, and Smeed (1973) reported that on British roads in 1972 about 15% of injury-causing automobile accidents involved an overtaking vehicle. More recently Clarke, Ward, and Jones (1998) reported that overtaking accidents accounted for nearly 10% of fatal road accidents in Nottinghamshire, England. From these analyses, Clarke et al. concluded that “the majority [of these accidents] arose from a decision to start the overtake in unsuitable circumstances” (Clarke, Ward, & Jones, 1999, p. 849) and that “the problem stems from faulty choices of timing and speed for the overtaking maneuver, not a lack of vehicle control skills as such” (Clarke et al., 1998, p. 465).

Laboratory and field studies on overtaking have reached similar conclusions. In a closed-track driving study, Jones and Heimstra (1964) reported that drivers made as many overestimates (i.e., that there was more than enough time to pass safely) as underestimates when judging
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the last safe moment to pass another vehicle. There was also considerable intersubject variability in the ability to make this judgment. From their findings, Jones and Heimstra (1964) concluded that drivers are unable to make accurate judgments about the temporal gap that is necessary for safe overtaking and passing. Similarly, Gordon and Mast (1970) reported that drivers were not able to accurately estimate the distance required to pass: Estimation errors ranged from 20% to 50%. Underestimations of the required distance increased with driving speed; at 50 miles/hr (mph; 80.4 km/hr) drivers were underestimating the minimum safe distance on 68% of trials.

Wilson and Best (1982) monitored vehicles on a stretch of public road in England. More than 400 overtaking maneuvers were classified into different categories, such as “cutting in” and “piggy backing” (i.e., tailgating). The main finding was that drivers often engaged in dangerous behaviors such as flying overtaking (overtaking without a pause) and lane sharing (not going completely out of the lead car’s lane). These behaviors were often used to compensate for small temporal gaps with the oncoming vehicles. It was also reported that 14% of overtaking drivers used a gap size that was too small for a safe overtaking maneuver to be completed.

Visual Information Available for Overtaking

One reason for the high level of driver error involved in overtaking is the complexity of the visual judgments involved (Hills, 1980). The driver must simultaneously estimate the time to collision (TTC) with an oncoming car, monitor the TTC with the lead vehicle so as to avoid a rear-end collision, and estimate the time required to complete the overtake based on the current speed, road conditions, and knowledge of the capabilities of his or her own vehicle. As we will discuss, the sources of information used by drivers to make these estimates and control their vehicle during the overtaking maneuver are largely unknown. We will next turn to a discussion of visual information that the driver could use to perform this dangerous task.

Accurate information about the TTC with the lead vehicle and oncoming cars is theoretically available to the driver under most conditions (the cases in which it is not are described in detail later). The time to collision with an approaching car is given by

\[
TTC = \frac{\theta}{\frac{d\theta}{dt}},
\]

in which \( \theta \) is the lead (or oncoming) vehicle’s instantaneous angular subtense and \( \frac{d\theta}{dt} \) is its instantaneous rate of increase of angular subtense (Hoyle, 1957). Research on how accurately observers can estimate TTC on the basis of Equation 1 has yielded mixed results. A large number of studies (including some that have involved judgments made while traveling in a moving car) have shown that observers make large (20%–40%) underestimates of TTC, with the magnitude of underestimation depending on a variety of factors, including approach speed, gender, age, and driving experience (reviewed in Gray & Regan, 1999b; Groeger, 2000). However, more recently we have shown that these large errors may be an artifact of the experimental methodology used (discussed in Gray & Regan, 2003). When the procedure was designed so that Equation 1 provided the only reliable information to perform the experimental task, estimation errors ranged from only 2% to 10%. In driving, TTC information appears to be particularly important for the initiation and control of braking (van Winsum & Heino, 1996; Yilmaz & Warren, 1995).

In some driving situations it has been found that the time headway (TH) appears to be a more important control variable than is TTC (Lee, 1976; van Winsum, 1998; van Winsum & Heino, 1996). The distinction between TTC and TH can be best understood by considering 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. However, 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. Van Winsum and Heino (1996) have reported that when following another vehicle, drivers regulate their speed to maintain a fixed value of TH that varies from driver to driver depending on skill level (i.e.,
more skilled drivers prefer a shorter TH). We have previously discussed the optical specification of TH and how it can be computed by the human motion-in-depth processing system (Gray & Regan, 2000); however, we are unaware of any research that has examined how accurately observers can estimate this quantity.

It has been demonstrated that the perception of the relative speed of self-motion is influenced by the visual information provided by the global optic flow rate and the edge rate (Larish & Flach, 1990); however, these visual cues do not provide accurate information about absolute speed. (In order to estimate absolute speed on the basis of the global optic flow rate or the edge rate, the driver would need to know the absolute distances of the objects that are creating the optical flow.) Field studies have consistently demonstrated that drivers cannot accurately estimate their speed of travel: “errors in subjectively estimating speed are sufficiently great that drivers should consult speedometers” (Evans, 1991, p. 128). Studies using verbal estimates of speed (reviewed in Groeger, 2000) and studies using a procedure that requires drivers to adjust their speed to a specified level (e.g., halve their current speed; Denton, 1976, 1977) have shown that speed estimates are highly inaccurate (errors range from 10 to 60 km/hr) and are easily biased by factors such as the driving speed on the previous trial.

There are two primary sources of information that a driver could use to estimate the absolute distance of another vehicle on the roadway, although both sources of information are very limited. The vergence angle of the eyes provides accurate distance information for an object that is fixated; however, because this source of information is effective only for objects nearer than about 10 m, it would not be useful for most driving situations. It also been suggested that drivers could use the angular size of the retinal image as a cue to absolute depth for familiar-sized objects such as cars and pedestrians (Stewart, Cudworth, & Lishman, 1993). However, usage of this cue could lead to dangerous estimation errors if the driver incorrectly identifies the object that is being approached (e.g., mistake a child pedestrian for an adult or mistake the type of car). Consistent with this theoretical analysis, empirical studies have demonstrated that drivers are quite inaccurate when estimating absolute distance. Observers consistently underestimate absolute distance: Estimated distance was a power law function of the absolute distance with an exponent of roughly 0.8 (Groeger, 2000; Teghtsoonian & Teghtsoonian, 1969).

The research reviewed so far has primarily examined performance in conditions in which visual information is accurate and reliable. Another possible source of errors of judgment is that in some situations the information provided by the human visual system is inaccurate. For example, a driver’s estimates of speed, TTC, and distance can be distorted by fog (Snowden, Stimpson, & Ruddle, 1998). For objects with a small angular size (e.g., a motorcycle viewed from a distance of 300 m), observers cannot accurately estimate TTC from Equation 1 because the object’s rate of expansion is near the detection threshold. Hoffmann and Mortimer (1996) have estimated the threshold value of $dθ/dt$ for driving to be roughly 0.003 rad/s and have shown that $dθ/dt$ can be well below this value in many driving situations. We have previously shown that staring straight ahead during simulated driving on a straight open road can give the driver the illusion that the TTC (and TH) with other vehicles is longer than it really is (Gray & Regan, 2000). This closing speed aftereffect is quite distinct from the well-known adaptation of the perceived speed of self-motion that is caused by the expanding retinal flow pattern (Denton, 1976; i.e., drivers underestimate their driving speed following adaptation).

To summarize, accurate visual information for TTC is available to the driver, whereas information about absolute driving speed and the absolute distance of other vehicles is lacking in most driving situations. Laboratory and field research has shown that under optimal conditions drivers can accurately estimate TTC but cannot accurately judge their own speed of travel. Under nonoptimal conditions (e.g., closing speed adaptation or for small objects), TTC estimation can also be highly inaccurate.

**Aims of the Present Study**

From this brief review it is clear that overtaking is a dangerous maneuver in which driver judgment errors can occur and that there are numerous potential sources of these errors. A
limitation of previous research in this area is that behavioral models of overtaking (like those developed for other driving tasks such as curve negotiation [Godthelp, 1986] and braking [Yilmaz & Warren, 1995]) are lacking. In order to reduce the number of accidents in these situations it is crucial to understand the perceptual-motor control and decision-making processes involved in overtaking so that these areas can be addressed in driver training and highway engineering.

The purpose of the present study was three-fold: (a) to investigate the visual-motor control strategies used when overtaking a lead vehicle, (b) to investigate decision making in overtaking, and (c) to investigate the effect of closing speed adaptation on these processes. In Experiment 1 we investigated overtaking of a lead vehicle with no oncoming traffic, and in Experiment 2 we added oncoming traffic traveling at different approach speeds.

**EXPERIMENT 1**

**Purpose**

The purpose of Experiment 1 was to investigate the visual-motor control strategies for overtaking a single lead vehicle and to examine how performance is affected by closing speed adaptation produced by prolonged driving on a straight open road (Gray & Regan, 2000). From previous research on car following (van Winsum, 1998; van Winsum & Heino, 1996), we predicted that drivers would use a control strategy of initiating overtaking of the lead vehicle when the time headway (TH) reached a critical value. We envisaged that there would be large inter-subject variability in this critical TH value (van Winsum, 1998). Finally, we predicted that closing speed adaptation (Gray & Regan, 2000) would reduce the TH value at which overtaking was initiated.

**Method**

*Apparatus.* The experiment was performed in a fixed-base driving simulator consisting of two main components: the frontal two thirds of a Nissan 240SX convertible and a 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 using a Barco 800G projector and was continually changed at an average rate of 20 frames/s in correspondence with the movement of the car. A texture pattern resembling black cracks on a grey background was mapped onto the surface of the road. The sky was dark blue and the surrounding ground was green, so that 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 4 m wide and subtended approximately 10° at the eye at a virtual distance of 20 m from the front bumper of the car. To aid the driver in assessing the 3-D motion of the car, short (0.5-m height) white posts 10 m apart were placed along the edges of the road. Other vehicles in the driving scene had a red body, gray windshield, and black tires and always followed a path down the center of the right lane. The distance down the roadway at which the other vehicles first appeared and their traveling speed were varied as described in the next section. The driving simulator provided some kinesthetic feedback through the torque in the steering wheel and audio feedback in the form of engine noise that grew louder as car speed increased.

*Procedure.* Each experimental session began with a 10-min practice trial designed to allow drivers to become comfortable with driving in the virtual environment. During this session, drivers drove on a roadway with several curves and there were no other vehicles on the road. The driving scene during the overtaking portion of the experiment was as follows. Drivers drove along 4000 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, we divided the roadway into 20 segments, each 200 m long. During the first 200-m segment there were no other vehicles on the road. Among the remaining 19 segments, a lead vehicle appeared in 12. The segments in which another vehicle appeared were chosen randomly. The lead vehicles’ initial distances (as measured from the beginning of the particular 200-m road segment in which they appeared) ranged from 65 to 85 m, and their speeds ranged from 65 to 10 m/s. Drivers were instructed to slow down when overtaking other vehicles. The lead vehicles’ initial distances (as measured from the beginning of the particular 200-m road segment in which they appeared) ranged from 65 to 85 m, and their speeds ranged from 65 to 10 m/s. Drivers were instructed to slow down when overtaking other vehicles.
20 m/s (i.e., from 32 to 45 mph). All of these vehicles traveled at a constant speed.

During overtaking maneuvers, drivers 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 that they should not go into the left lane too early because there might be cars coming the other way (this never actually occurred in Experiment 1). No feedback was given as to the success of their overtaking maneuver.

Prior to the each overtaking session, drivers completed one of the following two conditions: static scene (Condition 1) and adaptation to closing speed (Condition 2). In Condition 1, drivers sat in the car and looked at an unmoving road scene for 5 min. No explicit fixation instructions were given other than to keep looking at the screen. During this 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. Immediately following this period, drivers completed one 4000-m overtaking session. Drivers were instructed to begin driving forward immediately after they heard the tone.

In Condition 2, participants drove on a straight textured road with no other vehicles for 5 min. They were instructed to drive at any speed that 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. On the basis of our previous research (Gray & Regan, 1999a; Regan & Beverley, 1978, 1979), we predicted that the expanding retinal flow pattern produced by driving straight ahead would cause adaptation near the center of the road that was greater than 3 times $SD_{\text{empty}}$. We focused on overtaking initiation because this seems to be when the majority of driver errors occur; it is rare that an accident is caused by loss of vehicle control during the overtaking maneuver (Clarke et al., 1999).

To test our hypothesis that adaptation to closing speed would alter overtaking maneuvers, we initially analyzed two variables: (a) the TH at which overtaking was initiated (termed the critical TH throughout this paper) and (b) the participant’s driving speed at the point of initiation.

To examine the control strategies used by individual drivers, we fitted curves to the critical TH data for each participant and measured the slope and goodness of fit. In particular, we wanted to compare our predicted constant TH strategy with a constant distance strategy. (We chose not to evaluate TTC because in many cases our drivers initiated overtaking from a car-following position – i.e., so that their speed was roughly equal to the that of the lead car. In such cases TTC is infinite.) These two strategies make very different predictions about how the timing of an overtaking maneuver will vary with driving speed. On one hand, if a driver initiates overtaking at a constant distance from the lead car ($D_c$), the critical TH should follow Equation 2:

$$\text{critical TH} = \frac{D_c}{\text{speed}}. \tag{2}$$

In other words, the critical TH should become
smaller as driving speed increases. On the other hand, if a driver initiates overtaking at a constant TH with the lead car (THc), driving speed will have no effect on the timing of overtaking maneuvers, and

\[ \text{critical } TH = K, \]

in which \( K \) is a constant for any given driver.

**Participants.** Eighteen drivers participated in Experiment 1. 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. Drivers 1, 4, 5, 7, 9, 10, 12, 16, and 18 were women. Drivers 2, 3, 6, 8, 11, 13, 14, 15, and 17 were men. All participants except for Driver 2 (author RG) were naïve to the aims of the experiment and were paid an hourly rate.

**Results**

The mean critical TH and speed at the onset of overtaking averaged across the 18 observers are shown in Table 1. The overall analysis of the critical TH data revealed that the critical TH in the adaptation to closing speed condition was significantly smaller than in the static scene condition, \( t(17) = 5.7, p < .001 \). In addition, there was a significantly higher driving speed in the adaptation to closing speed condition than the static scene condition, \( t(17) = -3.4, p < .001 \).

To further understand the cause of these overall effects, we next analyzed the data of individual drivers. For clarity we grouped these analyses according to the three overtaking initiation strategies that we observed: (a) constant TH strategy, (b) constant distance strategy and (c) dual strategy.

**Constant TH initiation strategy.** The open circles in Figure 1 show critical TH values for 12 different overtaking maneuvers made by Driver 1 as a function of the forward speed at the onset of the maneuver. These data are for the static scene baseline condition. On the one hand, if this driver used a strategy of initiating overtaking at a constant value of TH (Equation 3), critical TH should be roughly constant for all speeds. On the other hand, if a constant distance strategy (e.g., expression 2) was used, the value of critical TH should decrease with increasing speed (i.e., negative slope). The slope of the line of best fit to the data shown with a solid line (-0.02) suggests that a constant TH strategy was used by this driver. Similar results were obtained for 7 of the remaining 17 drivers (designated Drivers 2–8). Slope values for the line of best fit were close to zero for these drivers (ranging from 0.05 to –0.12). A two-tailed \( t \) test revealed that the mean slope for the line of best fit (averaged across these 8 drivers) was not significantly different from zero, \( t(12) = 1.5, p > .1 \). The mean critical TH values for Drivers 1 through 8 (calculated from the intercept of the line of best fit) are plotted with open bars in Figure 2. The critical TH these drivers used for overtaking ranged from 1.3 to 4.9 s. This large intersubject variability in choice of critical TH is consistent with the previous findings from car following (van Winsum, 1998).

The solid circles in Figure 1 show critical TH values for Driver 1 in the adaptation to closing speed condition. As was the case in the static scene condition, data for this driver corresponded closely to a constant TH strategy. The slope of the line of best fit to the data was –0.02. A comparison of the solid and dashed curve fits in Figure 1 shows that this driver initiated overtaking at a considerably lower (by 530 ms on average) value of TH in the adaptation to closing speed condition. A two-tailed \( t \) test revealed this difference to be significant, \( t(14) = 4.8, p < .001 \).

Similar results were obtained for 6 of the 7 other drivers who used a constant TH strategy in Experiment 1. The mean critical TH values for the adaptation to closing speed condition are plotted with solid bars in Figure 2. Critical TH values were significantly shorter (marked with an asterisk) in the adaptation to closing speed condition than in the static scene condition for Driver 2, \( t(14) = 4.8, p < .001 \); Driver 4, \( t(14) = 5.7, p < .001 \); Driver 5, \( t(14) = 2.5, p < .025 \);

| TABLE 1: Mean Critical TH and Speed at Onset of Overtake in Experiment 1 |
|-----------------|-----------------|-----------------|
|                 | Static Scene    | Adaptation to Closing Speed |
| Critical TH     | 2.2 (0.23)      | 1.79 (0.18)      |
| Speed           | 24.9 (1.05)     | 29.8 (1.12)      |

Driver 6, \( t(14) = 1.8, p < .05 \); Driver 7, \( t(14) = 5.7, p < .001 \).
Figure 1. Critical time headway (TH) as a function of driving speed for Driver 1. Open symbols and the solid line are for the static scene condition. Solid symbols and the dashed lines are for the adaptation to closing speed condition. The solid and dashed lines are curve fits for a constant TH initiation strategy using TH values of 1.74 and 1.13 s, respectively.

Figure 2. Mean critical time headway (TH) for Drivers 1 through 8, who used a constant TH initiation strategy. Error bars show ±1 standard error. Statistically significant differences between the two conditions are indicated with asterisks.
There was no significant difference between the critical TH values for Driver 3.

**Constant distance initiation strategy.** Open circles in Figure 3 show critical TH as function of speed for Driver 9 in the static scene condition. The large decrease in critical TH with increasing driving speed suggests that this driver used a constant distance strategy rather than a constant TH strategy. The curve fit for Equation 2 using a $D_c$ value of 56.4 m, shown by the solid line, produced an $R^2$ value of .73. Similar results were obtained for two additional drivers (designated Drivers 10 and 11). The corresponding $R^2$ values for these drivers were .69 and .75, respectively. The mean critical distances for Drivers 9 through 11 are plotted with open bars in Figure 4. The critical distance for overtaking ranged from 54 to 61 m for these three drivers.

Adaptation to closing speed had a markedly different effect on these 3 constant distance strategy drivers (9–11) than on the constant TH strategy drivers (1–8) described previously. The solid symbols in Figure 3 show critical TH values following adaptation for Driver 9. As was the case in the static scene condition, this driver’s data are fit well by a constant distance curve fit (dashed line in Figure 3). This curve fit generated an $R^2$ value of .74 and a constant distance of 56 m. There was no significant difference between the critical distance for the static scene condition and the critical distance for the adaptation to closing speed condition, $t(14) = 0.16, p > .5$. Similar results were obtained for the other two drivers who used this control strategy. The mean critical distance values are plotted for Drivers 9 through 11 as solid bars in Figure 4. There was no significant change in the critical distance used for overtaking for Driver 10, $t(14) = 1.1, p > .2$, and Driver 11, $t(14) = 0.6, p > .5$.

**Dual initiation strategy.** Solid circles in Figure 5 show critical TH as function of speed for Driver 12. This driver appeared to use two different strategies, depending on the driving speed. For speeds less than 22 m/s, the data correspond very closely to a constant distance strategy with a critical distance of 53.4 m (shown by the sloped solid line). For speeds greater than 22 m/s, the overtaking data are fit well by a constant TH strategy with a critical TH of 2.04 s (shown by the flat solid line). The $R^2$ value for this two-line curve fit (.84) was greater than the $R^2$ value produced by fitting the constant distance strategy (.68). Six additional drivers (designated Drivers 13–18) showed a similar pattern. The results of curve fitting for Drivers 12 through 18 are shown in Table 2.

Open bars in Figure 6a show the estimated speed at which the overtaking strategy switched from constant distance to constant TH. This value ranged from roughly 18 to 24 m/s. Open
Figure 4. Mean critical distance for Drivers 9 through 11, who used a constant distance initiation strategy. Error bars show ±1 standard error. There were no significant differences for the two conditions.

Figure 5. Critical time headway (TH) as a function of driving speed for Driver 12. The solid and dashed lines are curve fits for a constant distance initiation strategy using distance values of 56.4 and 55.9 m, respectively.
bars in Figure 6b plot the critical distance values, and open bars in Figure 6c show critical TH values for speeds above the estimated strategy-switching value.

Adaptation to closing speed also had an effect on the overtaking maneuvers made by drivers who used a dual strategy. The solid circles in Figure 5 show the critical TH values following adaptation to expansion for Driver 12. This driver's data are fit well by a two-line curve fit (dashed line in Figure 5) using a constant distance strategy with a distance value of 53.5 m for speeds below approximately 23.5 m/s and a constant TH strategy with a TH value of 1.88 s for speeds greater than 23.5 m/s. This dual-strategy curve fit generated an $R^2$ value of .94, whereas a constant distance strategy curve generated an $R^2$ value of only .87.

The solid bars at the far left of Figures 6a through 6c plot, respectively, the estimated switching speeds, critical distances, and critical TH values for the static scene condition. A comparison of solid and open bars in Figure 6 reveals that adaptation to closing speed had two effects on overtaking maneuvers for Driver 12: The critical value of TH was lowered (Figure 6c) and the estimated strategy-switching speed was increased (Figure 6a). A two-tailed t test revealed that the mean critical TH in the static scene condition was significantly lower than the mean critical TH in the adaptation to closing speed condition for Driver 12: $t(10) = 2.2, p < .05$. Because we generated only one estimate of switching speed per condition for each driver, we could not analyze these data for each driver individually. However, the mean switching speed averaged across Drivers 12 through 17 was significantly higher in the adaptation to closing speed condition than in the static scene condition, $t(4) = 2.4, p < .05$. Finally, for Driver 12, there was no significant difference in critical distance for the two conditions (Figure 6b), $t(5) = 0.1, p > .5$.

Similar results were obtained for 5 of the 6 other drivers who used a dual strategy (Drivers 13–17). The curve-fitting results for these drivers are shown in Table 3. The solid bars in Figures 6a through 6c show, respectively, the estimated switching speeds, critical distances, and critical TH values for these drivers. The estimated switching speed was higher following adaptation for all 5 of these drivers. The critical TH values for the static scene condition were significantly higher than the critical TH values in the adaptation to closing speed condition for these drivers: Driver 13, $t(8) = 10.1, p < .001$; Driver 14, $t(12) = 1.8, p < .05$; Driver 15, $t(10) = 1.9, p < .05$; Driver 16, $t(10) = 2.7, p < .01$; Driver 17, $t(9) = 5.0, p < .001$. Note that the degrees of freedom were different for these statistical tests because each observer had a different number of observations below their estimated switching speed. There were no significant differences in the critical distance for the two conditions ($p > .2$).

The main effect of adaptation to closing speed for Driver 18 was to cause him to completely change his driving strategy. In the adaptation to closing speed condition, results for this driver most closely corresponded to a constant TH strategy, and there was no evidence of a dual strategy. The solid bar on the right side of Figure 6c shows the mean critical TH used by this driver in the adaptation to closing speed condition. This value was significantly lower than the critical TH value found with the static scene (open bars): $t(11) = 3.8, p < .001$.

Driving speed. Finally, we analyzed the effect of adaptation to expansion on driving speed for individual drivers. Figure 7a shows the mean driving speed at the onset of overtaking for Drivers 1 through 8. All 8 drivers in Figure 7a drove faster following adaptation. The difference in driving speed was significant for 6 of the 8 drivers (marked with an asterisk in Figure 7a): Driver 1, $t(14) = 4.4, p < .001$; Driver 3, $t(14) = 1.9, p < .05$; Driver 5, $t(14) = 5.7, p < .001$; Driver 6, $t(14) = 2, p < .05$; Driver 7, $t(14) = 4.0, p < .001$; and Driver 8, $t(14) = 2.4, p < .05$.

### Table 2: $R^2$ Values for Two Different Initiation Strategies in the Static Scene Condition for Drivers 12–18

<table>
<thead>
<tr>
<th>Driver</th>
<th>Constant Distance Strategy</th>
<th>Dual Strategy</th>
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<tbody>
<tr>
<td>12</td>
<td>.68</td>
<td>.84</td>
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<tr>
<td>13</td>
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<td>14</td>
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<td>18</td>
<td>.72</td>
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*Note: The $R^2$ values are shown for each driver for both the constant distance strategy and the dual strategy.*
Figure 6. (a) Estimated strategy switching speeds, (b) mean critical distances, and (c) mean critical TH values for Drivers 12 through 18. Asterisks show statistically significant differences between the two conditions. NA indicates these values were not applicable, because a dual strategy was not used in the adaptation to closing speed condition. Error bars show ±1 standard error.
Similar results were obtained for the drivers who used a constant distance strategy. Mean speeds for these drivers are plotted in Figure 7b. The mean driving speed was significantly greater following adaptation to expansion than following viewing a static scene for all 3 drivers: Driver 9, \( t(14) = 2, p < .05 \); Driver 10, \( t(14) = 2.8, p < .01 \); Driver 11, \( t(14) = 3, p < .001 \).

The effect of adaptation to closing speed on driving speed was very different for drivers who used a dual strategy. The mean driving speeds are shown in Figure 7c for Drivers 12 through 18. Driver 17 was the only driver in this group who drove significantly faster in the adaptation to closing speed condition than in the static scene condition, \( t(14) = 5.33, p < .001 \), and it should be noted that as described previously, this driver appeared to switch to a constant TH strategy following adaptation. This driver’s switch in driving strategy could be explained partially by his very large increase (11 m/s) in driving speed following adaptation; this increase may have been so large that all maneuvers in the adaptation to closing speed condition were made at a driving speed well above this driver’s switching speed.

Driver 13 drove significantly slower following adaptation to expansion, \( t(14) = 2.5, p < .05 \), and for Drivers 12, 14, 15, 16, and 17 there was no significant difference in driving speed for the two conditions.

**Discussion**

**Driving strategies.** Evaluation of simulated overtaking maneuvers revealed large individual differences in the control strategies used for initiation of overtaking with no oncoming traffic. Our drivers used three different control strategies. The data for 8 out of 18 drivers fitted a strategy of initiating overtaking of a lead vehicle at a constant TH (Equation 3). Another 3 participants in the present study used a constant distance strategy for the initiation of overtaking (Equation 2). Finally, the remaining 7 drivers used a dual strategy of initiating overtaking at constant distance when driving at slow speeds and initiating overtaking at a constant TH when driving at fast speeds. From the sample used in the present study, we could not identify factors related to the choice of strategy; however, it would be interesting for future research to examine whether factors that have been shown to influence choice of TH in car following (e.g., driving experience, reaction time, age, and personality traits such as “sensation seeking”; van Winsum, 1998; van Winsum & Heino, 1996) also are related to individual differences in overtaking strategy.

**Effects of adaptation to closing speed.** Simulated driving on a straight empty road for 5 min led to several changes in overtaking maneuvers for drivers in three strategy groups. Drivers in the constant TH strategy group initiated overtaking at a substantially smaller TH following adaptation than they did after viewing a static scene. Similarly, when driving speed was above their strategy-switching speed, dual-strategy drivers initiated overtaking at smaller values of TH following adaptation. The mean percentage change in critical TH for the constant TH strategy group (19.5%, \( SE = 3% \)) and the dual-strategy group (16.7%, \( SE = 4% \)) were both similar to the percentage change in TTC estimates following adaptation to expansion (20.8%, \( SE = 2% \); Gray & Regan, 1999a). The implications of these effects for highway safety will be discussed.

We propose that this decrease in the critical TH for these drivers is attributable to an overestimation of the time headway with the lead vehicle produced by adaptation to expansion. Regan and Beverley (1979) have shown that detection thresholds for motion in depth 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. Furthermore, these threshold elevations were of sizes similar to those produced by adapting to changes in the size of a small square (Regan & Beverley, 1978), a type of

<table>
<thead>
<tr>
<th>Driver</th>
<th>Constant Distance Strategy</th>
<th>Dual Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>.87</td>
<td>.94</td>
</tr>
<tr>
<td>13</td>
<td>.52</td>
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<tr>
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<td>.80</td>
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<td>17</td>
<td>.69</td>
<td>.83</td>
</tr>
</tbody>
</table>

**TABLE 3: \( R^2 \) Values for Two Different Initiation Strategies in the Adaptation to Closing Speed Condition for Drivers 12–17**
Figure 7. Mean driving speeds at the onset of overtaking for (a) critical TH strategy drivers, (b) constant distance strategy drivers, and (c) dual-strategy drivers. Asterisks show statistically significant differences between the two conditions. Error bars show ±1 standard error.
adaptation that we have shown also causes drivers to overestimate TTC (Gray & Regan, 1999a). In the present study, the focus of expansion of the adapting pattern (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. Therefore we predicted that our closing speed adaptation condition would cause drivers to overestimate TTC (and TH) with the lead vehicle. The temporal shifts in overtaking maneuvers, like that shown in Figure 1, are consistent with this prediction. In an earlier adaptation study, we provided further support for this “overestimation of TH model” (Gray & Regan, 2000).

Closing speed adaptation also had two speed-related effects on overtaking maneuvers. Ten out of 18 of our drivers (including all 3 drivers who used a constant distance strategy, 6/8 of the drivers that used a constant TH strategy, and 1 dual-strategy driver) drove significantly faster following adaptation as compared with the static scene measurements. These findings are consistent with the previous research by Denton (1976, 1977, 1980) in which it was found that prolonged exposure to simulated forward motion produces underestimations of perceived speed.

The underestimation of perceived speed following adaptation to simulated forward motion reported by Denton (1980) is also consistent with another of the main effects reported here: the increase in the estimated switching speed for the dual strategy drivers. If dual-strategy drivers use an estimate of perceived speed to determine whether to use a constant TH or constant distance overtaking strategy, an underestimation of perceived speed could explain the increases in the switching speed following adaptation to expansion, like those shown in Figure 7a. However, this shift in switching speed could also be explained at the level of motion-in-depth detectors without reference to perceived speed. If dual-strategy drivers switched between TH and distance based on the strength of the motion in depth signal produced by the lead vehicle, the reduction of sensitivity to motion in depth following adaptation to a radially expanding flow pattern (Regan & Beverley, 1979) would also predict an increase in the switching speed strategy.

Finally, it is evident from Figure 6b that the distance used by constant distance strategy drivers to initiate overtaking did not change following adaptation to expansion, suggesting that the adaptation did not alter the perceived distance of the lead vehicle.

**EXPERIMENT 2**

**Purpose**

The two main goals of Experiment 2 were (a) to investigate visual motor control strategies and driver decision making when overtaking a lead car in the presence of oncoming traffic and (b) to investigate the effect on these processes of adaptation to closing speed. From previous overtaking research (e.g., Gordon & Mast, 1970; Wilson & Best, 1982), we predicted that drivers would make a substantial number of errors in judging whether or not it was safe to pass.

**Method and Procedure**

The procedure and apparatus used were identical to those used in Experiment 1 except for the following. Each driver completed the following four conditions: (a) static scene/overtaking maneuver, (b) static scene/overtaking judgment, (c) closing speed adaptation/overtaking maneuver, and (d) closing speed adaptation/overtaking judgment. The static scene and closing speed adaptation conditions were as described for Experiment 1. Participants were instructed to always obey the posted speed limit of 65 mph (29 m/s). Specifics of the conditions were as follows:

**Overtaking maneuver.** Following the initial 5-min period, a lead car appeared on the road ahead. Participants were instructed to adjust their speed so as to follow the lead car. After 5 s of following, a brief auditory tone was played and an oncoming car appeared on the roadway. Participants were instructed that when they heard the tone they should overtake and pass the lead car when it was safe do so (i.e., either before or after the oncoming car had gone by). Following each overtaking maneuver participants drove for 200 m (656 feet) on an empty road before approaching another lead car to be followed and passed. Each trial consisted of 10 overtaking maneuvers.

**Overtaking judgment.** This condition was
identical to the overtaking maneuver except that rather than executing the overtaking maneuver, participants made a passive judgment. After participants followed the lead car for 5 s, an oncoming car appeared on the roadway. At a variable time after this car appeared, an auditory tone was played. Participants were instructed that when they heard the tone they should press one of two response buttons on the steering wheel to indicate whether or not at that instant there would be sufficient time to pass before the oncoming car arrived. They were further instructed to respond as quickly as possible, and response time was measured. After a response was received, all cars disappeared from the roadway and the participant drove on a straight empty road for 200 m (656 feet). Each trial consisted of 10 overtaking judgments.

The speed of the lead car was varied randomly between 9 and 18 m/s (20–40 mph). The speed of the oncoming car was varied between 20 and 31 m/s (45–70 mph). The distance of the oncoming car at the point when the auditory tone was played ranged from 200 to 400 m (656–1312 feet). All observers completed five trials for each of the four conditions.

Participants. Eighteen drivers participated in Experiment 2. All observers were experienced drivers with a minimum of 3 years of driving experience. Participants ranged in age from 18 to 43 years with a mean age of 23.1 years. None of the participants participated in Experiment 1.

Data analysis. The calculation of the safety margin required for the overtaking maneuver is illustrated in Figure 8a. We first calculated the distance required to overtake ($DRO$) based on the participant’s current driving speed ($S$) in miles per hour using the equation

$$DRO = 112.2 + 15.2S + 0.093S^2$$  \hspace{1cm} (4)$$

from the study of real driving by Gordon and Mast (1970). We then calculated the time required to overtake ($TRO$) using the participant’s current driving speed and the simulated car’s acceleration model. For this calculation we assumed that all drivers would pass the lead car at the maximum speed of 65 mph (29 m/s) – that is, we did not use the actual time and distances used by the participants to overtake. Finally, we calculated the time it would take the oncoming car to reach the critical distance required to pass (TTC) based on its speed and distance.

Results

Overall analysis. Figure 8b plots the number of overtaking maneuvers that were initiated for different safety margins. Data are plotted as function of TTC – TRO and are grouped into 0.9-s ranges of this variable. For all values less than 0 s, an overtaking maneuver could not be completed without a collision unless the participant exceeded the speed limit or the oncoming vehicle decreased its speed. We defined this range to be unsafe. Only maneuvers that were initiated in front of the oncoming car are shown. Of the 900 total trials (18 drivers $\times$ 50 repeats), it was safe to pass in front of the oncoming car (i.e., TTC – TRO was greater than zero) on 506 trials (56%).

We first analyzed data from the static scene condition (solid bars). For this condition, participants in our study initiated overtaking on 519 trials; 425 (84%) of these overtakes were safe and 84 (16%) were unsafe. This percentage of unsafe maneuvers is similar to the 14% reported by Wilson and Best (1982) in an analysis of real driving. The mean (TTC – TRO) at which overtaking was initiated was 2.6 ($SE = 1.9$) s for the 18 participants. The present findings are consistent with previous research that has shown that drivers are often inaccurate when judging whether or not it is safe to overtake (Gordon & Mast, 1970). Unsafe overtaking maneuvers will be analyzed in more detail later.

The pattern of results in the judgment condition was similar for the overtaking condition, although overall performance was worse for the judgment task. The solid bars in Figure 9 plot the number of “yes” responses (“it is safe to initiate an overtaking maneuver at this instant”) for different ranges of the variable TTC – TRO in the static scene condition. It was safe to pass in front of the oncoming car (i.e., TTC – TRO was greater than zero) on 510/900 trials (57%). Our participants judged that it was safe to overtake on 696 trials; 490 (70%) of these judgments were safe and 206 (30%) were unsafe. The mean (TTC – TRO) value for “yes” judgments was 2.1 ($SE = 3$) s. Thus our drivers made considerably more unsafe overtaking judgments than unsafe overtaking maneuvers. Statistical comparison of
the maneuver and judgment conditions will be described later. We next examine the effect of closing speed adaptation.

The open bars in Figure 8b plot the number of overtakes that were initiated in the adaptation to closing speed condition. It is clear from this figure that the distribution of overtaking maneuvers was shifted rightward in the adaptation condition. Participants initiated overtaking before the oncoming car arrived on 494 trials in the adaptation to closing speed condition; 349 (71%) of these overtakes were safe and 145 (29%) were unsafe. Closing speed adaptation substantially increased the total number of unsafe overtaking maneuvers that were initiated as compared with the baseline condition (142 vs. 84); statistical analysis of this effect is described later. The mean \((TTC - TRO)\) at which overtaking was initiated was significantly lower in the adaptation condition \((1.4 \text{ s, } SE = 1.9 \text{ s})\) than in the static scene baseline condition, \(t(17) = 2.15, p < .025\), thus creating a smaller margin for error for the overtaking maneuver.

**Figure 8.** (a) Calculation of safety margin for overtaking maneuvers. The distance required (shown by the fine line running perpendicular to the lane divider) for the participant (white car) to overtake and pass the lead vehicle was calculated from real driving performance data (Gordon & Mast, 1970). The time required for the driver to overtake \((TRO)\) was then compared with the time required for the oncoming car to reach this critical distance \((TTC)\). (b) Number of overtaking maneuvers initiated for different ranges of the value of \(TTC - TRO\). Filled bars show data for the condition in which observers adapted to closing speed by driving on a straight empty road prior to overtaking. Open bars show data for the no-adapt baseline condition. \(TTC - TRO\) values less than zero were defined as unsafe.
Similar results were obtained for the overtaking judgment condition (Figure 9). The open bars in Figure 9 show the number of “yes” responses (“it is safe to initiate an overtaking maneuver”) in the adaptation to closing speed condition. In this condition, participants judged that it was safe to overtake on 680 trials; 406 (60%) of these judgments were safe and 274 (40%) were unsafe. The mean (TTC – TRO) value for “yes” judgments was significantly lower in the adaptation condition (1.1 s, SE = 2.3 s) than in the static scene baseline condition, $t(17) = 3.1$, $p < .01$.

Reaction times for overtaking judgments were significantly longer (by 32 ms on average), $t(17) = 1.8$, $p < .05$, and had significantly larger variance, $F(17, 17) = 3.5$, $p < .01$, in the adaptation to closing speed condition as compared with the static scene condition. These increases in reaction time and in variability presumably arose because adaptation greatly reduced the oncoming car’s perceived rate of expansion (Regan & Beverley, 1978, 1979), which was already small because of its small initial angular size. We have previously shown that the processing of motion in depth and TTC is degraded when an object’s rate of expansion is near the detection threshold (Gray & Regan, 1998).

Overall data were analyzed using a $2 \times 2 \times 13$ repeated measures analysis of variance (ANOVA) with task (maneuver vs. judgment), condition (static scene vs. adaptation to closing speed), and TTC – TRO range as factors. For the TTC – TRO variable, the 13 levels shown in Figure 9 were used. The main effect of task was significant, $F(1, 17) = 12.3$, $p < .01$, indicating that our drivers judged it was safe to overtake more frequently than they initiated an overtaking maneuver. The main effect of TTC – TRO range was also significant, $F(12, 204) = 12.2$, $p < .001$. A trend analysis revealed that there was a significant quadratic trend, $F(1, 204) = 8.8$, $p < .01$, for this variable. On the surface this trend may seem unexpected; in particular it is surprising that there were not more overtakes initiated for large positive values of TTC – TRO (e.g., greater than 5.0 s). This effect could at least be partially attributable to the fact that the oncoming car’s rate of expansion was frequently below threshold when TTC – TRO was large. There was also a significant Condition $\times$ TTC – TRO Range interaction, $F(12, 204) = 10.4$, $p < .001$. From
Figures 8 and 9 it is clear that this interaction is attributable to the shift in the distribution produced by adaptation to closing speed.

**Overtaking strategies.** We next examined possible visual-motor control strategies a driver could use in this situation. From the findings of Experiment 1 of the present study and previous accident analyses (Clarke et al., 1999), we identified three possible strategies a driver could use to judge whether or not it was safe to pass from a vehicle-following position:

1. **temporal margin strategy:** initiate an overtake if the value of \( \text{TTC} - \text{TRO} \) is greater than some critical value (e.g., greater than zero);
2. **distance strategy:** initiate an overtake if the distance of the oncoming car is greater than some critical value; and
3. **time to collision strategy:** initiate an overtake if the \( \text{TTC} \) of the oncoming car is greater than some critical value.

In order to compare these three strategies, we isolated experimental conditions in which the different control strategies should conflict. For example, for an oncoming car speed of 29 m/s (65 mph) and a lead car speed of 18 m/s (40 mph), the value of \( \text{TTC} - \text{TRO} \) is –6.0 s when the distance of the oncoming car is 350 m. In this situation, temporal margin information would indicate overtaking is highly unsafe whereas distance information may indicate that it is safe to pass (in many driving situations an overtaking maneuver can be completed in less than 200 m).

Using this approach, we first compared the temporal margin strategy with the distance strategy by analyzing conditions in the present experiment for which the distance of the oncoming car was large (greater than 200 m) and the value of \( \text{TTC} - \text{TRO} \) was less than zero. To perform this analysis we divided the time series of each overtaking maneuver into 1-s bins. We then calculated the distance, \( \text{TTC} \), and \( \text{TRO} \) for each 1-s interval. Table 4 shows an example for one particular maneuver made by Driver 19. In this table it can be seen that the criterion of a large distance and negative \( \text{TTC} - \text{TRO} \) value was met during the first five 1-s intervals. On average, this situation occurred during at least one interval for 36/50 trials per driver (the value ranged from 34 to 39 trials across the 18 drivers because of randomized presentation). Figure 10a shows the percentage of overtakes that were initiated for these situations for all 18 drivers (e.g., a percentage of 100% indicates that in every instance that this situation occurred the driver initiated an overtake). It is clear from this figure that our drivers clustered into three distinct groups. For 2/18 drivers (Drivers 19 and 20), there was a relatively high proportion (>60%) of overtakes in these situations, suggesting that these drivers were primarily using a constant distance strategy. For 10/18 drivers (Drivers 21–30), overtakes were rarely (<6% of the time) initiated under these circumstances, suggesting that these drivers were using a temporal margin strategy. For the remaining 6 drivers (Drivers 31–36), the percentage of overtakes initiated was intermediate (30%–45% of the time) between these two extremes.

To further understand the strategies used by our drivers, we subdivided the data shown in

<table>
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<th>Time From Tone Onset (s)</th>
<th>Distance of Oncoming Car (m)</th>
<th>TTC of Oncoming Car (s)</th>
<th>TTC – TRO (s)</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>8</td>
<td>71.4</td>
<td>1.52</td>
<td>–15.8</td>
</tr>
</tbody>
</table>

Note. \( \text{TTC} \) = time to collision, \( \text{TRO} \) = time required to overtake.
Figure 10a into conditions in which the rate of expansion of the oncoming car was above the threshold value of 0.0025 to 0.003 rad/s (Hoffmann & Mortimer, 1996) and conditions in which this value was below threshold. Figure 10b plots the percentage of overtakes that were initiated when the rate of expansion of the oncoming car was above (solid bars) and below (open bars) threshold. Whether this value was above or below threshold had little effect on the behavior of the distance strategy drivers (Drivers 19 and 20). However, it had a large effect on the behavior of Drivers 31 through 36; the percentage of overtakes initiated when the rate of expansion was below threshold was considerably higher than the percentage when the rate of expansion was above threshold. Thus this group of drivers appeared to use a dual strategy of initiating an overtake based on the distance of the oncoming car when its rate of expansion was below threshold and using the value of TTC – TRO when its rate of expansion was above threshold. The temporal margin strategy drivers did not consistently make more unsafe overtaking initiations when the rate of expansion was below threshold, indicating that these drivers waited until the visual
information was above threshold before deciding whether or not to pass.

We next compared the temporal margin strategy and the TTC strategy: Were the drivers who appeared to be using temporal range in Figure 10a (i.e., Drivers 21–30) actually just using the TTC of the oncoming car? To answer this question, we analyzed data for conditions in which the value of TTC − TRO was below zero and the value of TTC for the oncoming car was large (>10 s). On average, this situation occurred during at least one 1-s interval for 10/50 trials per driver. For Drivers 21 through 30, there was a very small percentage of overtakes initiated in this condition (ranging from 0% to 10% for the 10 drivers), suggesting that these drivers were basing their decision to overtake on the value of TTC − TRO rather than on the TTC of the oncoming car.

**Discussion**

Consistent with previous laboratory (Gordon & Mast, 1970) and field research (Wilson & Best, 1982), our drivers frequently made inaccurate decisions about whether it was safe to overtake in front of an oncoming vehicle. In baseline conditions, unsafe overtaking maneuvers were initiated on 16% of trials and unsafe yes/no judgments were made on 29% of trials. The finding that our drivers made significantly more unsafe overtaking judgments than unsafe maneuvers could partially be explained by our criterion for the initiation of an overtake. Because we defined an overtake as a lateral maneuver greater than three times the standard deviation for straight driving, it is possible that our drivers could make a decision to overtake, begin moving into the passing lane, and then subsequently change their decision before this criterion was reached. Possible explanations for driver error in this situation will be discussed.

Adaptation to closing speed produced by 5 min of driving on a straight open road had a dramatic effect on overtaking behavior. Our drivers made significantly more unsafe maneuvers and unsafe judgments, and the value of TTC − TRO at which overtaking was initiated was significantly smaller. Furthermore, overtaking judgments were significantly more variable following adaptation and were significantly slower. These findings demonstrate that closing speed adaptation impaired the ability of our drivers to decide whether or not it was safe to initiate an overtaking maneuver.

Similar to the results of Experiment 1, here we found that our drivers used three different control strategies for initiating overtaking in Experiment 2: a temporal margin strategy based on the value of TTC − TRO (56% of drivers), a distance strategy (11% of drivers), and a dual-distance/temporal margin strategy that depended on the rate of expansion of the oncoming car (33% of drivers). The proportion of drivers using these three different strategies was very similar to that found in Experiment 1 (no oncoming car), suggesting that drivers may use the same control variables in different driving situations.

**GENERAL DISCUSSION**

Why Do Drivers Make Errors When Overtaking?

Research on overtaking is rare in comparison with research on other driving behaviors, even though accidents in this situation can be quite common in some areas and are often serious. (The proportion of overtaking accidents resulting in death or serious injury in some areas in the United Kingdom is >20%.) In a recent study, Clarke et al. (1999) examined 402 overtaking accidents and found that for 272 (68%) of these accidents the precipitating error was a faulty “go” decision made by the overtaker. Given that drivers have little opportunity to learn and practice this difficult maneuver during driver training, this high degree of error in judging when it is safe to initiate an overtake is not surprising. In order to reduce the number of overtaking accidents, it is crucial to identify the sources of these errors.

Consistent with what is observed in real driving, drivers in our present study made a considerable number of errors during simulated overtaking maneuvers. These errors can be attributed to two primary causes: choice of driving control strategy and inaccurate perceptual information.

**Visual-motor control strategy.** When no oncoming traffic was present (Experiment 1), we found that a substantial proportion of our drivers used a control strategy of initiating overtaking at a critical distance with the lead car (17% of
our drivers used this strategy in all situations, and another 39% used it when driving at slow speeds). The use of distance as a control variable is problematic for several reasons. First and foremost, this strategy is not robust across situations. Consider the following example. For drivers in Experiment 1, the mean critical distance for overtaking was 165 feet (50 m). If a driver using this strategy was traveling at 29 m/s (65 mph) and the lead vehicle was stopped in the roadway (e.g., because of a mechanical breakdown), the TTC with the lead vehicle at the time the overtake was initiated would be only 1.7 s. Given that braking to avoid a collision with the stopped vehicle would require greater than 6 s (Lee, 1976), the driver would be at high risk for a rear-end collision if the overtake could not be completed (e.g., because of the sudden appearance of an oncoming car over a hill). The second major problem associated with using distance as a control variable is that as described earlier, previous research has shown that drivers cannot accurately estimate the absolute distance of another vehicle on the roadway.

Previous research on overtaking has chiefly focused on judgments concerning the oncoming car, and only recently has this research considered “the crucial interaction with the vehicle(s) being overtaken and not just the relationships with the oncoming traffic” (Clarke et al., 1998, p. 456). Wilson and Best (1982) observed that in many overtaking situations there were dangerously small gaps between the overtaking vehicle and the lead vehicle, and Clarke et al. (1999) reported that 37% of overtaking accidents involved a collision with lead vehicle. The results from Experiment 1 of the present study suggest that the use of a critical distance passing strategy may be a significant source of error in these situations.

When drivers were overtaking in the presence of an oncoming car (Experiment 2), we again found that a substantial proportion of our drivers used distance (in this case the distance of the oncoming car) as a control variable: 11% of our drivers used this strategy in all situations, and another 35% used it when the rate of expansion of the oncoming car was below threshold. Similarly, Farber and Silver (1967) reported that when an oncoming vehicle is at a large distance, drivers often assume that it is traveling at the speed limit, which leads to unsafe overtaking decisions. This choice of control strategy is dangerous for the reasons described earlier. Furthermore, it can explain a substantial number of the dangerous overtaking maneuvers that were observed in the present study. In the static scene condition, 84 unsafe overtaking maneuvers were initiated; the vast majority (82%) of these maneuvers were initiated when the distance of the oncoming car was greater than 250 m, suggesting that drivers were using a large oncoming car distance as a cue that it was safe to overtake.

In order to safely complete an overtaking maneuver, a driver must ensure that the time required for completion of the maneuver (i.e., the TRO in Figure 8a) is less than the time required for the oncoming car to reach the point in space where the maneuver will be completed (i.e., the TTC in Figure 8a). In other words, the only safe and robust strategy for controlling overtaking requires the usage of some form of temporal information. There are several possible reasons for the finding that a substantial proportion of drivers appear to not use temporal information. One problem could be the lack of driving training for overtaking maneuvers: It is possible that many drivers do not know that the distance of the oncoming vehicle is not a reliable source of information. Clarke et al. (1998) have reported that faulty decisions to overtake are particularly prevalent in younger drivers. Because no training or practice with overtaking is provided, it may be that the appropriate control strategy is acquired only through real-world driving experience.

Another reason many drivers do not use a temporal control strategy is that the visual information required is frequently inaccurate. Accurate visual information about TTC is available in some conditions (Gray & Regan, 2000), but in many driving situations this information can be below sensory threshold, degraded, or biased (this issue will be discussed in detail). When this temporal information is below perceptual threshold, the driver should not switch to using the distance of the oncoming car as a control variable; instead, he or she should wait until the appropriate visual information is detectable. Estimation of TRO is presumably based on the driver’s estimate of the current speed of self-motion and knowledge of the capabilities of the
vehicle being driven (e.g., the maximum acceleration). Gordon and Mast (1970) have shown that drivers often cannot estimate TRO accurately, particularly when traveling at high speeds. Because there are several circumstances in which a driver does not have the information needed to make a decision about whether or not it is safe to overtake, becoming a safe driver may require learning in which situations visual perception can and cannot be trusted (a similar problem is faced by pilots; see Wiener, 1988). This again could partially explain why young, risk-taking drivers seem to be at higher risk for overtaking accidents.

Inaccurate perceptual information. In the present study we were interested in overtaking following adaptation to closing speed. We have previously shown that this type of adaptation can cause overestimates of TTC with an approaching object (Gray & Regan, 1998) and can cause drivers to delay the initiation of simulated overtaking maneuvers (Gray & Regan, 2000). Adaptation to closing speed can occur when a driver gazes fixedly at the road or at an oncoming vehicle rather than scanning the scene ahead (Regan & Beverley, 1979). Our driving simulator results suggest that in real-world driving situations, closing speed adaptation may impair the ability of a driver to decide accurately whether they have sufficient time to complete a maneuver such as an overtake while avoiding collision with an oncoming car. Closing speed adaptation not only makes judgments slower but also substantially biases the driver toward an underestimate of the time required, thus increasing the probability of collision.

Consistent with Denton’s (1976) findings, we also found that adaptation to expansion can lead to increases in driving speed. Denton (1976) proposed that this increase in driving speed following adaptation may cause drivers to enter roundabouts and off-ramps at an unsafe speed. Although intuitively one might think that this increased speed would also increase the risk of an overtaking accident, it should be emphasized that this would not be the case for the majority of the maneuvers in the study reported here. Drivers using temporal variables as control strategies (either TH in Experiment 1 or TTC – TRO in Experiment 2) would not be adversely affected by driving at a higher speed (unless, of course, they drive fast enough to lose control of the vehicle) because they would initiate overtaking at a greater distance from the lead car when speed is increased, thus keeping the temporal margin constant. The risk of accident would be increased only for drivers using the constant distance strategy: Faster speeds would lead to small temporal gaps at the initiation of overtaking. Therefore, the misestimation of time to collision produced by adaptation to closing speed may have more serious consequences for road accidents than does underestimation of perceived speed. This is an important point because the stripes painted across the roadway (primarily in the United Kingdom) that are used to create a speed illusion that counteracts the effects of adaptation and reduces the actual driving speed (Denton, 1976) would not counteract the lengthening of time to collision caused by adaptation to expansion.

In many overtaking scenarios the rate of expansion of lead and oncoming vehicles can be below or near the detection threshold for changing object size (Hoffmann & Mortimer, 1996). Under these conditions drivers cannot accurately estimate the relative velocity between their own vehicle and the lead vehicle (Hoffmann & Mortimer, 1996) and, of more importance for the present discussion, cannot accurately or reliably estimate the TTC of an approaching car (Gray & Regan, 1998). When faced with this situation a substantial proportion of the drivers in the present study reverted to using the distance of the oncoming vehicle as a cue for initiating overtaking. Clearly this is not a safe strategy, and drivers must learn to wait until TTC information is above threshold in these situations.

Suggestions for Possible Safety Measures

The results of the present study suggest that the addition of instruction in overtaking maneuvers to driver training might reduce the prevalence of overtaking accidents. Driving simulations and/or filmed driving scenarios could be used to teach young drivers how to make a safe overtaking judgments based on temporal information and to identify dangerous situations in which their visual perceptions cannot be trusted (e.g., when the oncoming car’s rate of expansion is below threshold). Another possible safety measure
could be the addition of in-car driver aids that can measure the range and speed of the oncoming and lead vehicles (e.g., radar, laser, GPS) and provide a warning if the driver initiates an unsafe maneuver.

The dangerous state of being adapted to closing speed occurs when a driver gazes fixedly at the road or at an oncoming vehicle rather than scanning the scene ahead (a state commonly referred to as “highway hypnosis”). These conditions could be avoided by encouraging the driver to make more frequent eye movements. One possible method for achieving this would be to use an in-car eye tracker that would send a warning signal when there was a long period of fixation.

**Limitations and Future Research**

It is clear that the task used in the present study was a simplified simulation of real-world overtaking. In real driving, overtaking decisions must be made in the presence of hills, blind curves, dips, low light, glare, and/or poor weather conditions. Furthermore, the lead car can change speed and/or position (e.g., make a left turn) during the overtaking maneuver. Overtaking a lead car that is about to make a turn across the passing lane was the identified cause of 12% of accidents in the accident analysis by Clarke et al., 1999.) Therefore, the results from the present study may have underestimated the frequency of perceptual and decision-making errors in this task. However, in a driving simulator there are no real consequences for driving unsafely, and it has been shown that drivers are more risk taking and drive at higher speeds as compared with when they are actually driving (Kemeny & Panerai, 2003), which may lead to an overestimation of judgment error frequency. Clearly, the validity of using driving simulators to study complex maneuvers such as overtaking and passing needs to be addressed in future research.

Finally, in the present study we examined overtaking in the presence on oncoming traffic only when the overtake was initiated from a car-following position. Wilson and Best (1982) have reported that drivers frequently overtake without pausing behind the lead vehicle (“flying overtaking”). In the future we plan to directly compare these two different types of overtaking maneuver.

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