EXPERIMENTAL MEASUREMENTS OF PERCEPTUAL THRESHOLDS IN CAR-FOLLOWING

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A series of experiments was carried out to measure perceptual thresholds of drivers in car-following. Early results from pilot experiments revealed 2 basic difficulties associated with previous attempts reported in the literature to measure relative motion thresholds in car-following: First, it was sometimes possible for the subject to perceive the pitching of the lead car in response to the initiation of an acceleration or deceleration maneuver and thereby infer immediately that a change had occurred. Second, permitting the subjects to respond when they were sufficiently confident that they had detected a change introduced an unmeasurable variable. This unmeasurable variable arises because a subject wishing to make no errors might wait for larger stimuli than one wishing to register quick responses, even though both might have the same sensitivity. An experiment was designed to circumvent these difficulties. By means of an occlusion device, subjects seated as passengers in a following car traveling at 45 mph were given controlled looks, normally of 4-sec duration, at a lead car moving at a constant speed. For each exposure the subjects indicated whether they perceived negative (that is, the cars came closer) or positive relative motion. The results indicate that (a) the dominant cue used to judge the sign of relative motion is the average value of relative speed divided by spacing; (b) there is response bias in favor of indicating negative rather than positive relative motion; and (c) there is a high level of sensitivity to relative motion. For example, if a lead car were closing on a following car at 3 mph, the following driver's probability of correctly identifying the sign of relative motion as negative rather than positive after a 4-sec observation is 0.99 when the spacing is 200 ft.

ONE of the most frequently occurring situations confronting an automobile driver is following another vehicle. This situation occurs on 2-lane roadways and multiple-lane highways when passing is difficult or restricted and whenever a motorist is "content" to follow another vehicle with approximately the same desired speed. For more than a decade a number of investigators have attempted to construct theoretically and validate experimentally mathematical models of this driving task (1). Such models focus on the longitudinal task and neglect all other subsidiary tasks such as steering and routing. The form of these models is principally a stimulus-response type of equation. While the stimulus has been expressed by using several different mathematical forms, the relative speed (the difference between the lead-vehicle speed and the following-vehicle speed) as well as the intervehicle spacing have been shown experimentally to be important variables in the process and correlate well with the acceleration and braking of a vehicle.

Brown (2) as early as 1960 pointed out that, in the light of the results of experiments on car-following, there was need for information regarding the driver's sensitivity to, or discrimination of, relative motion. Indeed, the ability of a driver to estimate quantities such as spacing or changes in spacing and relative speed are implicitly assumed

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in "car-following" equations. The implication of the existence of thresholds to the perception of such quantities is that they establish limits to the applicability of such models.

Over the past several years a number of studies have been devoted to quantifying perceptual cues involved in longitudinal pursuit, not only in following an automobile but also in the closely related perceptual task of effecting a rendezvous in space by direct visual sensing.

These previous studies have been conducted in the laboratory (3, 4) using simple geometrical figures in an otherwise featureless environment, in simulators (5, 6), and in the field (7, 8, 9, 10) using automobiles. One of the major sources of difference between the real-world situation and that of laboratory experiments is that the driver, or subject, is moving through a visual environment that is crowded with extraneous details. This difference might well have a significant effect on detection of relative motion and underlines the need to conduct experiments in the real world. All the previous real-world experiments have used a similar technique. Two cars were driven at constant speed with the subject in the following vehicle. At some instant the lead car adopted a constant acceleration or deceleration, and it was the subject's task to indicate when he perceived some dynamic change. The results from these field experiments do not indicate good agreement with each other or with laboratory results. There was, therefore, a need for further experimental investigations.

PILOT EXPERIMENTS

One series of pilot experiments was conducted to investigate, at different following distances, a driver's ability to reproduce speed changes of a lead vehicle whose speed oscillated sinusoidally in time about a fixed value with a period of 20 sec and an amplitude of 7 ft/sec. Spectral analysis applied to the results showed that the maximum value of the cross-correlation coefficient decreased from 0.98 at a following distance of 75 ft to about 0.3 at 750 ft. The time lag (i.e., the value which maximized the cross-correlation) increased from 1.5 sec at a spacing of 75 ft to 7 sec at a spacing of 750 ft. Data were collected at following distances up to 1,280 ft. However, beyond 750 ft the results were erratic, sometimes with the cross correlation increasing and the time lag decreasing as the spacing became greater. It was difficult to determine from the vehicle trajectories or speed histories when the driver applied a control input. A major difficulty with this approach was that it was impossible for the subject to maintain a spacing that did not drift by large amounts during the run. A different approach was therefore adopted.

In this approach the subject rode as a passenger, observed the lead car that executed random changes in speed, and indicated by means of a 3-state switch whether he thought he was going faster, at the same speed, or slower than the car in front. The spacing (i.e., distance from front bumper to front bumper) was varied between 80 ft and 550 ft. The results from 2 subjects analyzed in detail showed clearly the pitfalls in offering subjects a 3-state choice (that is, permitting a "zero" or "don't know" option). For relative velocities too small to be reliably judged, one subject indicated zero relative motion approximately 20 percent of the time, independent of spacing, whereas the other subject indicated zero relative motion 80 percent of the time when the spacing was 140 ft. This figure decreased to 50 percent at a spacing of 500 ft. Such variability in the way subjects choose to perform the task makes it impossible to derive a clearly defined threshold value. A third choice allows each subject the degree of freedom to set his own level of performance. However, the results did indicate that, when the value of relative velocity divided by spacing exceeded a value of about $\pm 0.03\ \mathrm{sec}^{-1}$ independent of spacing, it was detected 75 percent of the time. The corresponding threshold value of angular velocity decreased from 13×10^{-4} rad/sec at a spacing of 140 ft to 2.2×10^{-4} rad/sec at a spacing of 460 ft.

RESPONSE TO PITCH OF LEAD VEHICLE

Upon examining the data for individual responses in the foregoing experiments, it was apparent that in many cases, independent of spacing, the response to an acceleration of the lead vehicle was almost instantaneous. It appears that in some cases the subject was able to perceive a change in attitude or pitch of the lead car at the onset of an acceleration. This was not readily apparent to subjects or experimenters during the initial experiments, but further tests in which such an effect was consciously looked for did reveal that frequently it was indeed possible to perceive the initiation of an acceleration through this mechanism. When a vehicle with a nonrigid suspension initially moving at constant speed starts to accelerate (or decelerate), the rear of the vehicle drops (or rises). This is particularly pronounced on acceleration because an attempt to manually produce a constant level of acceleration usually produces an instantaneous initial value higher than intended. If the driver is able to perceive this pitch, he could immediately infer a change. Such an effect would explain why, with the oscillatory speed profile experiment, the overall time lag decreased for large spacings, if one assumes that as the spacing increased the fraction of all responses of this type also increased. It is worth commenting that, in acceleration, exhaust cues could provide additional unintended information, although we did not observe any such effects in our experiment.

The observation of this pitch effect led us to consider if it had been present in any earlier work. A distribution of all the reaction times measured in the field by Torf and Duckstein (8) and Whitty and Duckstein (9) was examined and seen to have a distinctly bimodal shape, with one peak at about 1.7 sec and another at about 2.8 sec. It seems plausible that responses to lead vehicle pitch might have contributed to the peak about 1.7 sec, especially as the reaction times reported were not reduced by the time required to press a response button. Many responses to very small values of the stimulus are apparent in Figures 1 and 2 of Snider (10). It again seems plausible that some of these may be responses to vehicular pitch.

The findings from our pilot experiments underlined several difficulties associated with attempts to measure threshold information in the real driving situation. In the light of these, an experiment was designed to circumvent them.

EXPERIMENT

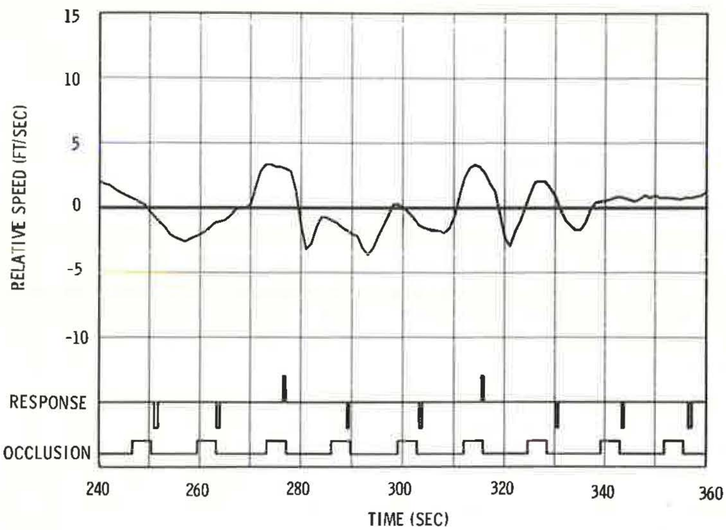
Two vehicles were driven on a single lane of roadway. By means of the eye occlusion device shown in Figure 1, subjects seated as passengers in a following car were given controlled looks, normally of 4-sec duration, at a lead car. The following car traveled at a nearly constant speed of about 45 mph, and during each exposure the lead car also traveled at a nearly constant speed close to this value. The subjects were thus presented with nearly constant relative speed stimuli. It was the lead driver's responsibility to control spacing and relative speed. Small random deviations from constant speeds led to measurable accelerations that were also analyzed. The subject's task was to judge whether the cars moved further apart (i.e., positive relative motion) or came closer together during the exposure period and to register his positive or negative response by moving a lever into one of two positions. No other options such as "zero" or "don't know" were permitted; in all cases the subject responded with his best estimate.

Ten subjects performed a total of 42 runs, each consisting of a 10-mile trip on a public freeway. Approximately 50 judgments per run were obtained (Table 3). Of the total of 2,170 judgments made, 1,923 had a 4-sec exposure time and 247 (data set 10[c] in Table 3), a 2-sec exposure time.

Both lead and following cars were fitted with fifth wheels that generated a pulse for each foot of forward travel, pulses for the lead vehicle being telemetered to the following car. The trajectory information, state of the occlusion device, and the subject response, together with a 3,000-Hz clock signal, were recorded synchronously by a multichannel magnetic tape recorder. The data were later reduced to digital format for computer analysis. A 2-min sample of the information recorded, representing about 1½ miles of forward travel, is shown in Figure 2, in which the state of the occlusion device ('up' indicates the subject was permitted to see), the subject response ('up' indicates that positive relative motion was judged), and the relative speed are plotted versus time. The plotted response time has been corrected to take into account a delay of 0.4 sec between the subject's decision to respond and the recording of the response. This value was obtained by using the instrumentation in the car to measure the time difference between a simple event (a light coming on) and the recorded subject response.

Figure 1. Eye occlusion device: (a) vision unobstructed; (b) vision occluded.

Figure 2. Sample (2 min, about 1½ miles) of computer plot of relative speed, state of occlusion, and subject response versus time. Numerical details for the exposure are given in Table 1 (top 9 rows).



The pertinent information concerning the judgments was punched on data cards, one card per response, and the analysis was performed using this data set. A short sample (which includes the nine judgments in Fig. 2) of this information is given in Table 1.

ANALYSIS

We assume that when the subject makes a judgment he is responding to some function of the dynamic variables to which he has been exposed. We refer to such functions as stimulus functions. One of our main aims is to identify which stimulus function most simply, consistently, and completely describes all the effects present in our data. The criterion adopted is that a good stimulus function is one for which the probability of judging positive relative motion (as distinct from negative relative motion) depends only on the value of the stimulus function and not explicitly on any of the independent variables, such as spacing. Ideally, all such dependence would be incorporated into the stimulus function.

The comparative ability of 9 different stimulus functions to explain the detection of the sign of relative motion, as recorded in our data, was investigated. The functions studied included 3 previously discussed in the literature—acceleration (7, 8, 9), angular velocity (11), and spacing change divided by spacing, $\Delta S/S$ (10)—as well as others indicated in Table 1. Scatter diagrams showing the values of these stimulus functions to which the subjects were exposed were plotted versus spacing. One such plot, for the stimulus function average relative speed divided by spacing (U/S), is shown in Figure 3 for all 2,170 items of data collected in the experiment. The subject response is represented by the symbols plotted; an "x" indicates that the sign of relative motion was correctly judged and an "o" indicates that it was incorrectly judged. The data clustered around 3 target spacings of 125, 250, and 500 ft. The distribution of the values of relative speed, U, was essentially the same at different spacings. The decreasing numerical value of the stimulus with increasing spacing in Figure 3 occurs because it is U/S and not U that is plotted. The reason for plotting U/S will be discussed later.

Figure 4 shows only those values of U/S whose sign was incorrectly judged. When the magnitude of U/S is greater than about 1×10^{-2} $\sec^{-1}$, errors are rare. However, small positive values of U/S are more likely to be incorrectly judged as negative than small negative values are to be incorrectly judged as positive. To examine these and other questions in a more quantitative manner the technique described in the following was adopted.

Technique

The range of the stimulus function of interest was divided into about 20 intervals of equal size, and the fraction of exposures in each cell that were judged positive, P^+, was plotted as a bar graph. A large number of such response plots were produced and formed the basis of our analysis. One example of such response plots is shown in Figure 5. Smooth curves were visually fitted to the bar graphs. The first, second, and third quartile points, Q_1, Q_2, and Q_3, were estimated from the fitted curves, that is, the values of the stimulus function when P^+ was 0.25, 0.5, and 0.75 respectively. The first quartile point, Q_1, is the value of the stimulus that is perceived negative 75 percent of the time and will be referred to as the negative threshold. The 0.5 point, Q_2, gives the value of the stimulus that is equally likely to be perceived negative or positive. As we shall see, Q_2 is not generally equal to zero but has a positive value that increases with spacing. As a result of this response bias, Q_3 is larger than the absolute value of Q_1 by an amount that also increases with spacing, thus rendering these quantities unsuitable for sensitivity-comparison purposes. A more suitable quantity that characterizes sensitivity is the intercategory threshold (12), defined as $I = Q_3 - Q_1$, which in our case measures the stimulus region in which the sign of relative motion cannot be detected correctly as often as 75 percent of the time.

In the foregoing we have considered the threshold to be the value that is correctly judged with probability 0.75. This choice is essentially arbitrary, and different levels have been adopted. The intercategory threshold at a given level will always be the difference between the positive and negative thresholds at the same level.

Table 1. Sample of the response data.

Subject Response	Time at End of Observation (sec)	Following Car Speed (ft/sec)	Values at Beginning of Observation			Values at End of Observation				Angular Velocity (10^{-4}rad/sec)	ΔS (ft)	$\frac{\Delta S}{S}$ (percent)	Exposure Time (sec)
			S (ft)	U (ft/sec)	A (ft/sec²)	S (ft)	U (ft/sec)	A (ft/sec²)	U/S (10^{-2} sec^{-1})				
-	250.4	67.4	181	0.7	-0.22	182	-0.5	-0.51	-0.3	-0.9	1	0.4	3.8
-	263.2	67.7	165	-2.2	0.17	158	-1.2	0.23	-0.7	-2.8	-6	-4.1	3.8
+	277.2	68.7	162	3.3	0.09	172	3.1	-0.12	1.8	6.2	10	6.0	3.8
-	289.7	68.7	168	-1.0	-0.21	164	-1.8	-0.21	-1.1	-4.0	-4	-2.6	3.8
-	302.8	67.4	145	0.3	-0.15	144	-1.2	-0.44	-0.8	-3.4	-1	-0.9	3.8
+	315.6	68.4	134	2.1	1.18	145	3.0	-0.52	2.1	8.5	11	7.3	3.8
-	328.4	67.5	142	0.6	1.08	149	1.8	-0.39	1.2	5.0	7	4.5	3.8
-	343.0	68.7	145	0.5	0.11	148	0.8	-0.03	0.6	2.2	3	1.8	3.9
-	355.6	68.6	154	0.8	-0.05	157	0.7	0.12	0.5	1.8	3	1.7	3.8
-	368.2	68.2	166	1.2	-0.06	170	0.8	-0.21	0.5	1.7	4	2.4	3.8
-	382.7	67.2	153	-5.4	-0.69	139	-4.7	1.18	-3.4	-14.7	-14	-10.4	3.9
+	395.9	68.8	127	1.6	0.97	138	3.2	-0.21	2.3	10.2	11	7.7	3.8
-	408.4	67.8	146	0.1	0.04	147	-0.1	-0.34	-0.1	-0.3	1	0.3	3.8
-	420.4	68.5	142	-0.6	0.00	141	0.2	0.31	0.2	0.7	-1	-0.7	3.7
+	433.7	67.5	141	-0.1	0.70	144	1.4	0.08	1.0	4.1	3	1.8	3.8
+	447.5	68.4	251	17.1	-1.68	278	13.7	-1.96	4.9	10.6	27	9.8	3.8
-	461.4	68.3	329	0.0	0.25	331	0.8	0.22	0.2	0.4	1	0.4	3.8
+	474.6	68.5	345	1.8	-0.03	349	0.9	-0.75	0.3	0.5	5	1.3	3.8
-	486.5	68.2	340	-0.6	0.21	337	-0.9	-0.26	-0.3	-0.5	-2	-0.7	3.7
-	498.7	65.9	325	-1.0	0.17	323	-0.4	0.04	-0.1	-0.2	-2	-0.5	3.7
+	511.8	68.9	317	0.1	-0.32	316	-0.9	-0.33	-0.3	-0.5	-1	-0.3	3.8
-	532.2	69.9	308	-1.5	-0.33	303	-2.4	-0.16	-0.8	-1.5	-5	-1.7	4.1
-	545.4	68.0	288	-1.0	0.05	285	-0.5	0.12	-0.2	-0.4	-3	-0.9	3.8
-	558.1	67.3	291	2.4	0.11	301	2.8	-0.07	0.9	1.9	10	3.4	3.8

Figure 3. Scatter diagram of average value of relative speed divided by spacing (10^{-2} sec^{-1}) versus spacing (feet) for all data collected in the experiment. The "x" indicates that the sign of the relative motion was correctly identified and the "o" indicates it was incorrectly identified.

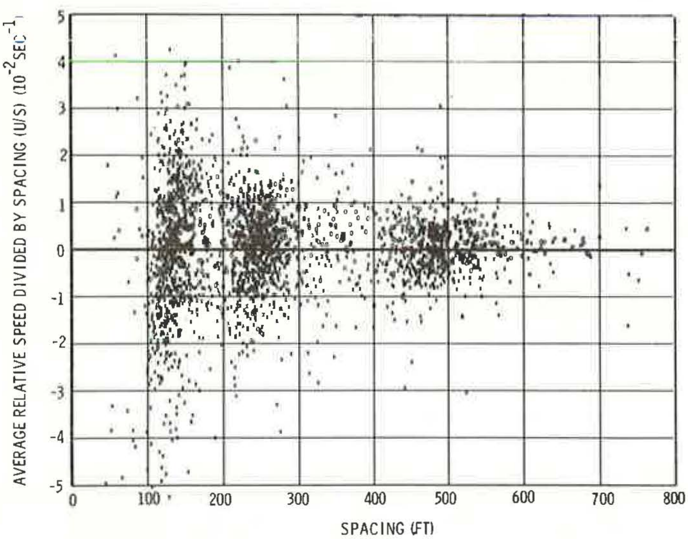


Figure 4. Scatter diagram of average relative speed divided by spacing (10^{-2} sec^{-1}) versus spacing (feet) for all exposures whose sign of relative motion was incorrectly judged.

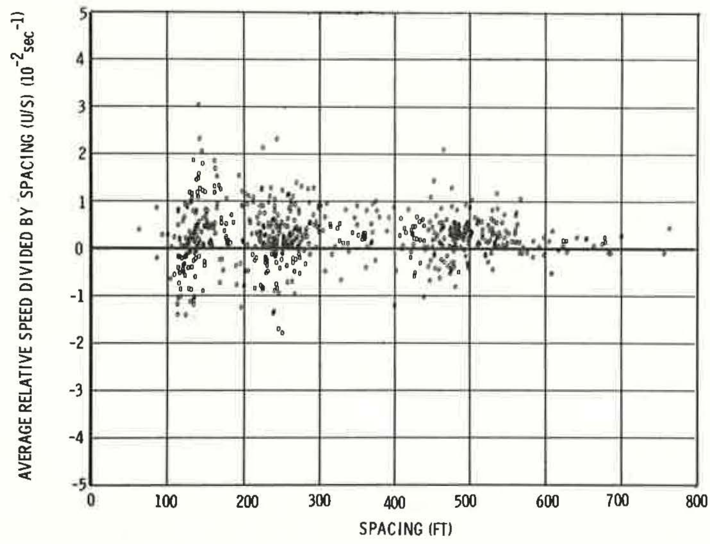


Figure 5. Response plot for the stimulus function average relative speed divided by spacing (10^{-2} sec^{-1}) for all the 4-sec exposure time data.

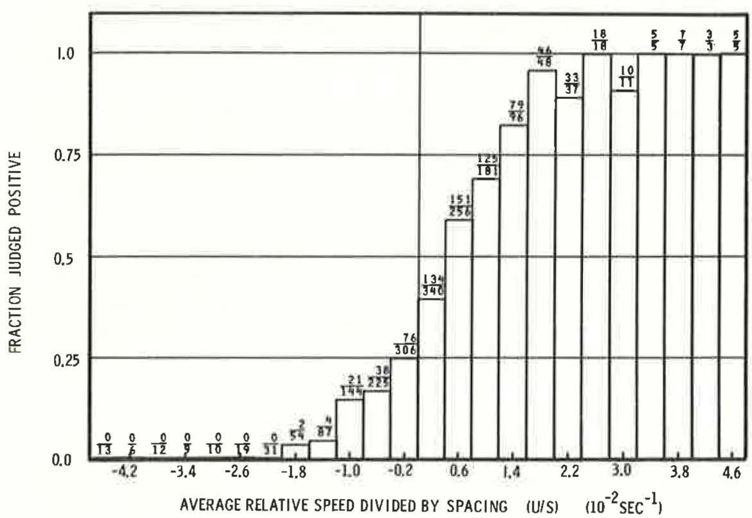


Table 2. Dependence on spacing of the value equally likely to be judged positive or negative (Q_2) and the intercategory threshold at the 0.75 level ($I = Q_3 - Q_1$) for the stimulus functions of relative speed, relative speed divided by spacing, and angular velocity (values are for end of observation).

Spacing Interval (ft)	No. of Data	Mean Spacing (ft)	Std. Dev. (ft)	Relative Speed (ft/sec)		Relative Speed / Spacing (10^{-2} sec^{-1})		Angular Velocity (10^{-4} rad/sec)	
				Q_2	I	Q_2	I	Q_2	I
131 ≤	317	115	16	0.1	1.8	0.15	1.4	1.8	7.4
131-156	283	142	7	0.4	1.8	0.5	1.8	2.3	5.8
156-226	332	192	24	0.6	2.9	0.5	1.6	1.7	4.1
226-256	302	240	8	1.0	3.0	0.45	1.45	1.0	2.9
256-350	315	286	26	1.2	5.0	0.5	1.6	1.2	2.9
350-484	318	439	37	3.4	7.0	1.0	1.9	1.2	2.6
>484	303	540	58	3.8	6.6	0.65	1.2	1.0	2.2

RESULTS

Spacing Dependence

All 2,170 responses were divided into 7 spacing intervals, and the intercategory thresholds, I, and response bias, Q_2, were measured (Table 2) for the stimulus functions of relative speed, relative speed divided by spacing, and angular velocity, in all cases using the instantaneous values at the termination of the observation. By angular velocity we mean the rate of change of the angle subtended by the lead car at the subject's eyes. These 3 functions are essentially US^n, where n has the values 0, -1, and -2 respectively. Only when n = -1 is the intercategory threshold independent of spacing. Therefore, on the basis of the criterion discussed earlier, we reject all functions with an S^{-2} spacing dependence (angular velocity) and all with an S^0 spacing dependence (relative speed and spacing change). The constancy of the intercategory threshold of relative speed divided by spacing indicates that the stimulus function that best describes the detection of the sign of relative motion has reciprocal spacing dependence.

Acceleration and Exposure Time Dependence

Small variations in the speed of both cars produced measurable accelerations. The probability that an exposure with a given value of acceleration was judged positive was independent of acceleration within the range covered by our data (approximately -1 ft/sec^2 to 1 ft/sec^2). It is therefore concluded that acceleration is not a major cue to the sign of relative motion. However, acceleration did systematically influence the perception of other stimulus functions. For example, the dependence on acceleration led to rejecting the hypothesis that the subject was responding to the value of the relative speed at the beginning of the observation divided by the spacing. The response plots for 2 reciprocal spacing functions were independent of acceleration. These are the average value of the relative speed divided by spacing (U/S) and spacing change divided by spacing (ΔS/S).

Comparing the data from a 2-sec exposure with those for a 4-sec exposure indicates that the responses to both of these are exposure time-dependent. Preliminary results indicate that the dependence for U/S is perhaps slightly less. The remaining results will therefore be presented as responses to U/S, bearing in mind that the same value of U/S is more likely to be correctly judged after a longer exposure. Figure 6 shows the quartile points and intercategory threshold of U/S plotted for the data divided into 11 spacing intervals. The constancy of the intercategory thresholds for this function over a wide range of spacing is apparent. The response plot for all the 4-sec data is shown in Figure 5. The stimulus values are readily converted to ΔS/S (in percent) by multiplying by 4 since (U/S)T = ΔS/S where T is the exposure time.

Response Bias

There was a pronounced and consistent bias in favor of indicating negative, rather than positive, relative motion. For there to be an equal probability of indicating negative or positive relative motion a positive relative motion must be present. All values of Q_2 in Table 2 are positive, whereas in the absence of a bias we would expect them to be distributed around zero. The response curves for all the data in the current experiment indicate that, when presented with zero relative motion, the probability that negative motion is judged is 0.66 and not 0.5 as we would expect in the absence of any bias. This bias in favor of indicating negative relative motion is much larger than could be explained by an effect resulting from physical asymmetry in the closing as compared to the opening situation. The magnitude of the response bias for stimulus functions with reciprocal spacing dependence increases with spacing (Table 2 and Fig. 6).

Individual Subject Results

The data for individual subjects were divided into the 3 spacing intervals, 100-190, 200-320, and 380-640 ft. The quartile points, Q_1, Q_2, and Q_3, were estimated for the stimulus function U/S and ΔS/S. The values of the intercategory threshold, I, and re-

Figure 6. Response bias, positive, negative, and intercategory thresholds for the stimulus function average relative speed divided by spacing (10^{-2} sec^{-1}) plotted versus spacing (feet). This was obtained by dividing all the data into 11 spacing intervals.

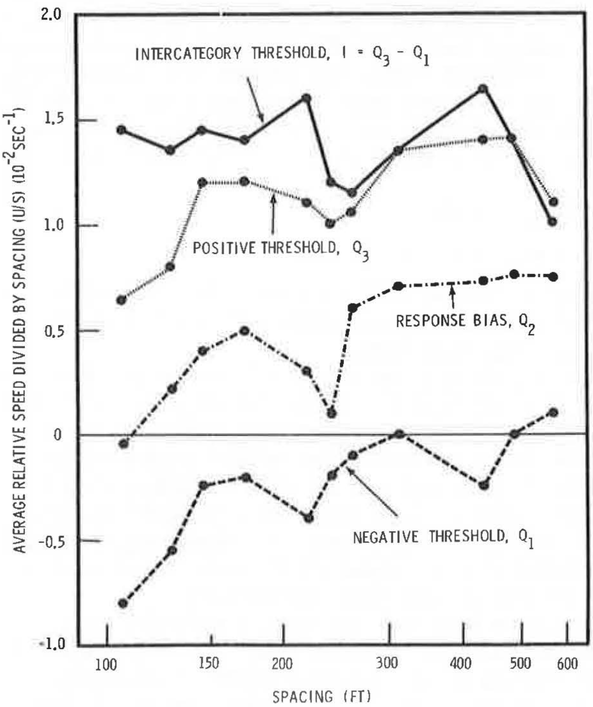


Table 3. Values equally likely to be judged positive or negative (Q_2) and intercategory thresholds at the 0.75 level ($I = Q_3 - Q_1$) for the stimulus function U/S (10^{-2} sec^{-1}) for the individual subjects in 3 spacing intervals and for all spacings combined.

			Spacing Interval							
			S = 100 to 190, $\bar{S}$ = 139 ft		S = 200 to 320, $\bar{S}$ = 249 ft		S = 380 to 640, $\bar{S}$ = 489 ft		All Spacings, $\bar{S}$ = 279 ft	
Subject No.	Data Set	No. of Data	Q_2	I	Q_2	I	Q_2	I	Q_2	I
1	1	63	-0.1	1.4	0.5	0.5	–	–	0.1	1.6
2	2	99	0.3	1.2	0.6	0.6	0.6	1.1	0.4	1.6
3	3	208	0.1	0.6	0.5	1.1	0.5	1.5	0.4	1.0
4	4	200	-0.2	1.0	-0.1	0.9	0.4	0.7	0.1	0.9
5	5	208	0.6	1.6	0.3	1.4	0.4	1.4	0.7	1.7
6	6	97	0.6	0.3	0.4	1.0	–	–	0.6	0.8
7	7	211	0.7	2.0	0.1	1.3	0.4	1.5	0.3	1.6
8	8	214	0.6	0.9	0.3	1.7	0.3	1.5	0.5	1.4
9	9	196	-0.3	1.3	0.3	0.8	0.7	1.1	0.3	1.1
10	10[a]	207	-0.2	1.5	0.9	1.2	0.9	1.6	0.6	1.7
10	10[b]	220	0.8	1.2	0.6	1.3	1.0	0.7	0.7	1.0
10	10[c]	247	0.6	2.0	0.7	1.2	0.7	1.4	0.9	1.8
Mean			0.29	1.24	0.42	1.08	0.59	1.25	0.47	1.36
Standard deviation			0.41	0.53	0.27	0.34	0.23	0.33	0.25	0.36

[a]Four runs with procedure identical to that used for other subjects.
[b]Four runs with 4-sec exposure from extra session.
[c]Four runs with 2-sec exposure from extra session.

sponse bias, Q_2, for the variable U/S are given in Table 3 for the 3 spacing intervals and for all spacings combined. Wherever a blank entry occurs in this table it indicates insufficient data. The constancy of I and the increase of Q_2 as the spacing increases, as previously shown for all the data, are apparent for individual subjects. For all spacings combined, each and every subject has a positive value of Q_2. The values of I obtained by combining all spacings tend to be larger than the mean from the 3 spacing intervals. This is because the increase of Q_2 with spacing contributes additional variance to the response curves. For all spacings combined, the variation in I between subjects is slightly more than a factor of 2. However, when one subject was tested twice, a variation almost as great as this was observed (see results for data sets 10^a and 10^b in Table 3). This suggests that the observed variations could reflect both varying performance levels for each subject or differences in sensitivity from subject to subject.

CONCLUSIONS

There are three major conclusions from this study:

1. The response of the subject in detecting the sign of relative motion is to the average value of relative speed divided by spacing (U/S). The same level of U/S is more likely to be judged correctly after a longer exposure time.
2. There is bias in favor of indicating negative, rather than positive, relative motion. In addition, this negative response bias is an increasing function of spacing. The bias is in the direction of increased safety, in that the driver sometimes will think he is gaining on the car in front when in fact he is not. The unsymmetrical nature of the risk associated with different control decisions is not a plausible explanation of the observed bias, because the sign indicated by the subject under the conditions of the experiment in no way affected any control input to the following car. However, it is still conceivable that such a bias, learned through driving experience, is so strong that it continued to operate for each subject even though they were passengers.
3. The results of the experiment indicate a high level of sensitivity to the sign of relative motion. For example, the response curves indicated that, if a lead car were closing on a following car at 3 mph, the following driver's probability of correctly identifying the sign of relative motion as negative rather than positive after a 4-sec observation is 0.99 when the spacing is 200 ft. It therefore seems unlikely that driver limitations in the detection of the sign of relative motion could be a serious contributor to rear-end collisions or such accidents as a stationary car on a freeway being struck from the rear. Such accidents are more likely manifestations of problems of attention and the inability to correctly judge the magnitude of relative motion. That is, the driver has no doubt he is gaining on the lead car but is insufficiently aware of the rate at which he is gaining. The results also indicate that little improvement in smoothness of flow or safety is likely to be obtained by providing the driver with information on the sign of relative motion without also giving its magnitude.

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DISCUSSION

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It is certainly important to learn more about driver sensitivity to various cues and to be able to define which cues he may be using in carrying out various driving tasks. The longitudinal control task of the vehicle, as in car-following, is one that requires considerable attention because it occurs with high frequency under most driving conditions in this country and in others having large vehicle populations.

The cues used for relative motion thresholds have, as pointed out by Evans and Rothery, been studied by a number of researchers, and different absolute levels of driver sensitivity have been found because of methodological differences. Unlike the authors, I find that, although different methods have been used in these previous tests, there appeared to be a reasonable degree of correspondence in the findings for describing the perceptual process involved although not necessarily in the interpretations offered by the authors of those papers. For example, Braunstein and Laugherty (7) concluded that subjects were responding to the occurrence of an acceleration or deceleration in sensing relative velocity. But Hoffman (1966) reviewed their data and concluded that a Weber ratio model, $\Delta H/H$, where H is the distance headway between the vehicles, could explain the data quite well. According to this the drivers were responding to the change in the headway spacing between the vehicles.

Evans and Rothery have used a different methodology from that employed before because they felt that laboratory studies or field studies utilizing fairly conventional psychophysical methods run into difficulties because of either the simulation involved or the factors influencing the driver's judgments. However, their own method would reduce the driver's normal scanning behavior by providing limited opportunities for viewing the vehicle ahead. In addition, the subject is made aware of the fact that a judgment is required of him at a certain time, which is not analogous to the manner in which a driver would direct his attention to certain cues in normal driving. It is probably useful, overall, to conduct investigations using different methodologies, each of which can tap some aspects of the actual task.

The findings obtained in this study are of interest. The authors have concluded that the driver is highly sensitive to detecting the sign of a spacing change. Most of their experiment was carried out using a 4-sec exposure, which produced a high level of sensitivity, such that a relative speed of 3 mph at 200 ft was detected 99 percent of the time. The detection probability did decrease when a 2-sec exposure time was used.

We have conducted similar studies, using other procedures. One method used a laboratory simulation in which 2 lights, simulating the taillights of a vehicle, were moved toward or away from the observer at a constant speed. More recently we have used a dynamic car-following driving simulator for the same type of study. We have also conducted studies on the road in which a driver followed another vehicle, with both cars moving at the same speed but with the lead vehicle beginning to coast down at random intervals. The following car driver had to detect the onset of coasting. Incidentally, we used the same technique for measuring intervehicle headway by means of distance pulses obtained from fifth wheels. We commiserate with the authors of this paper in having suffered the tribulations associated with this method, even though it ultimately did work for us as it apparently did for them. Each of our experiments showed that a Weber ratio of the form $\Delta H/H$ was a good model for explaining the driver's detection of relative motion.

The authors have presented their results in terms of a model of average relative speed (U) divided by spacing (S) and have found that this is independent of the initial spacing. Since the function U/S is equivalent to the function $\Delta S/ST$, it can be seen that they have results that can be explained by the Weber model such as described earlier. This shows agreement with previous studies except for the value of the constant expressing the driver's sensitivity. For example, in my 1971 study the 50th percentile value of $\Delta H/H$ was about 0.12, whereas the 99th percentile performance, as reported in their study, was about 0.10. As mentioned previously, it was expected that greater sensitivity would be found in their study because of the use of the visual occlusion method and because their subjects were not also driving the vehicle or carrying out any side tasks.

The greater sensitivity of the method used by the authors leads them to conclude that driver limitations in detecting the sign of relative motion are not likely to be a serious contributor to rear-end collisions. While I would basically agree with this conclusion, our own data have shown that Weber ratios of as high as 0.4 were obtained in our test situations for less than 1 percent of responses, indicating an infrequent, but potential, hazard. As pointed out by the authors, there is little question that other problems such as poor visibility, expectancy, attention, and the inability to correctly estimate relative speed are important contributing variables.

From a more theoretical standpoint the choice of a "stimulus function" of U/S by the authors causes some difficulties to me as a psychologist. This is because it suggests that the driver is directly sensing the relative speed and the absolute headway spacing. The problem arises with the former, i.e., relative speed detection. The equation suggests that the driver can detect relative speed in some direct manner. It seems much more probable that drivers would estimate relative speed on the basis of the rate of change of the headway spacing. Thus it would appear much more satisfying to utilize the stimulus that is probably sensed by drivers in an underlying model that seeks to explain drivers' behavior. For this reason, and because the value U/S is difficult to grasp for intuitive meaning (at least the value S/U would be better, since this is the time headway), it would be recommended that the data be also represented by an alternative, but equivalent, model.

In conclusion, the authors have reported a good experiment using a method that should provide data with relatively low variability, although almost certainly overestimating the sensitivity of drivers in the traffic stream. For the benefit of other behaviorists, a performance measure in the form of a Weber function would be preferable to the one they have used.

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A basic consideration that must be weighed heavily in designing experimentation dealing with man's perceptual characteristics in automobile driving is that of the fidelity of the task presented to the subjects—i.e., are we studying man in the automobile driving context or are we generating an artificial task and hoping for a strong correlation between his performance on the artificial task and in the automobile driving task? In this paper, Evans and Rothery chose wisely in conducting their research in a "free field" environment with its wealth of related perceptual cues, which can only be guessed at in simulation. However, by restricting the subject's view of the leading vehicle physically through a visual occlusion device and temporally to a 4-sec "peek" (additional trials involving 2 sec were run with one subject), they have generated a task that is quite unlike the normal visual perception task in automobile driving. The authors' rationale for taking this approach is that indirect cues may be presented either from the leading vehicle's exhaust or from vehicle pitching due to spring wrap-up. However, the authors state that they were unable to maintain a constant relative velocity during the short time interval the subject had view of the leading vehicle and consequently considered acceleration itself as a possible cue in the course of their data analysis. Although the authors suggest that the direct perception of vehicle pitching during acceleration may have influenced subject performance in a study reported by me (10), subsequent research has demonstrated this not to be the case (13).

The basic advantage in using a modified method of constant-stimulus psychophysical technique, as Evans and Rothery have employed it, is that a forced choice response may be obtained in which the subject's subjective confidence in his response is eliminated from consideration—the data yield directly to probabilistic analysis, in which case a given threshold may be identified with a corresponding probability of detection (assuming the subject does not change markedly from one experimental session to the next). On the other hand, the method of adjustment technique allows the subject to respond when he is confident of what he is perceiving (perhaps at a level analogous with a 0.99 probability of detection threshold). I argue that the threshold appropriate for use in this context is a level that the subject views as necessary for initiating a response—after all, a driver will undoubtedly only initiate a control action in driving when he views that control action as necessary, based on his perception of the situation. The method of adjustment, when employed with carefully prepared instructions, appears to most adequately meet this need.

A review of the data shown in the authors' Figure 6 serves well to illustrate some of the conceptual problems associated with the probabilistic analysis of relative motion perception data. For example, the 0.75 negative response threshold, Q_1, is reported as corresponding with a value of average relative speed divided by spacing, U/S, of zero for data taken in the vicinity of 300 ft while the corresponding threshold is found to be either zero or actually positive for data taken for headways in excess of approximately 500 ft. In other words, as a consequence of using a binary forced-choice procedure, the subjects respond 75 percent of the time that relative motion is negative when it is in fact zero or positive at these separation distances. Now, if the authors believe this, and if a threshold level of 0.75 is selected, this implies that a driver would be either decelerating or preparing to do so whenever the relative velocity of his vehicle with respect to a leading vehicle is zero and the headway or separation is in the vicinity of 300 ft or greater than 500 ft. I have considerable difficulty in accepting this finding.

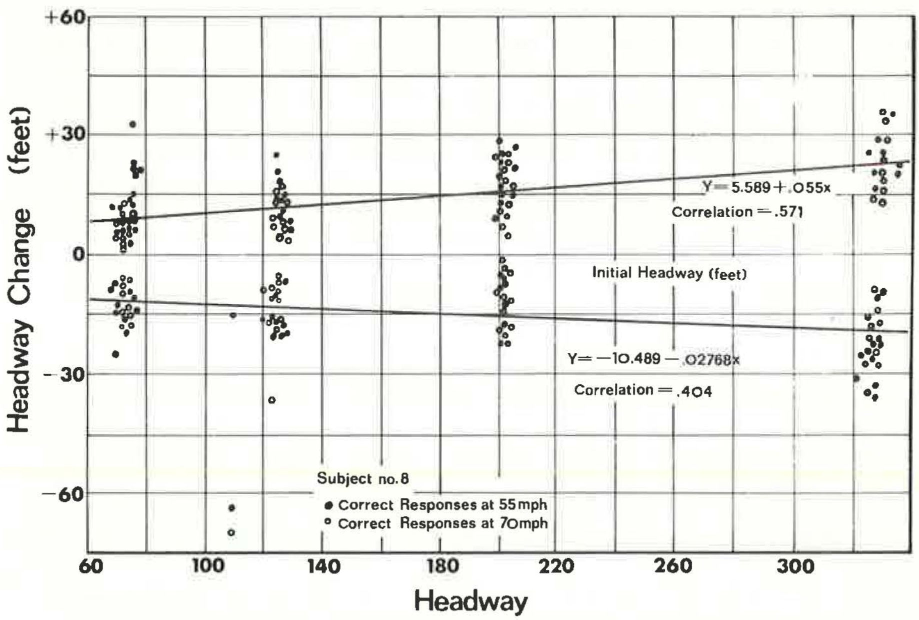
A stated conclusion of this research is that the probability of the subject's responding to a given stimulus is biased in the direction of favoring a response indicating a closure of the 2 vehicles. It is worth noting again that the subjects were forced to indicate either a positive or negative relative motion. In this context, because closure represents potential hazard and is the direction of change that is of more immediate concern to the driver, it appears both reasonable and likely that the driver's response would be biased in this direction when forced to respond at levels below his "level of confidence."

A major purpose of this paper has been to "identify which stimulus function most simply, consistently, and completely describes all the effects present in our data." Based on the fact that the ratio of average relative speed, U (feet per second), divided by spacing, S (feet), produces a function that has a relatively consistent intercategory threshold with respect to separation distance, the authors conclude that this function best describes all effects in the data. However, they note that this function does not describe the effects associated with the 2-sec exposure. Hence, the data are time-dependent. The authors further point out that, if their threshold value for this function is multiplied by exposure time, the resulting threshold is expressed in terms of a percent change in headway. In the case of the data presented in the authors' conclusions, this 0.99 threshold with a 200-ft separation corresponds with a $\Delta S/S$ of 8.8 percent or, in this case, a decrease in headway of 17.6 ft. It is of interest to note that, in a similar study (13) that involved constant relative acceleration (negative) coupled with a method of adjustment stimulus presentation, a mean headway change for detection was found to be 11.25 ft for original headways in the 180- to 190-ft range. This is the pooled average of 245 data points obtained from 8 subjects who performed while both driving and riding as passenger in the research vehicle. No statistical difference could be determined between the subject's performance when driving or riding as a passenger in the vehicle. It should be further noted that this writer has investigated (13) and reported on the effects of relative velocity as well as relative acceleration on the perception of relative motion between a leading and following vehicle at distances ranging from approximately 50 ft to 300 ft. These studies strongly indicate that for this range of separation distances, within which most car-following occurs, a stimulus function of the following form quite adequately describes all observed effects:

$$\Delta S = K_1 + K_2 S$$

Figure 7 shows this relationship with both raw data and corresponding stimulus functions. In the opinion of this writer, the authors' data would be more meaningfully described by this form of stimulus function, which is not time-dependent. (This assumes, of course, that the change occurs within a short enough time period so that the subject's memory trace of the initial separation distance is intact—changes taking longer than approximately 45 sec appear to exceed man's memory span.)

Figure 7. Relative velocity study—headway versus headway change.



Finally, the authors conclude that "there is a high level of sensitivity to relative motion." The authors' example to support this conclusion is that the probability of correctly identifying the polarity of a negative relative motion involving an initial separation of 200 ft with a closing relative velocity of 3 mph and a 4-sec observation is 0.99. As previously noted, this corresponds to an 8.8 percent decrease in separation distance; thus, based on the authors' findings, the separation distance must decrease by 8.8 percent for us to be 99 percent confident that the subject perceives the change. Couple this finding with man's motor response time and a realization that this type of data describes the best performance that man is capable of and then you begin to understand the underlying factors that result in the behavior exhibited by mass traffic flow. In this writer's opinion, the data do not support the authors' conclusion. In fact, just the opposite conclusion is indicated by both their data and the research of others.

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AUTHORS' CLOSURE

In our paper we have consciously striven to emphasize those aspects of driver perception that are of most concern to traffic theory and experimentation and therefore have avoided delving into the psychological and psychophysical aspects. Those aspects have been discussed in detail in a separate paper being published elsewhere (14). There we present our results in terms of analytical response functions to 2 stimulus functions, namely, average relative speed divided by spacing (U/S) and spacing change divided by spacing (ΔS/S). An analytical response curve is necessary because a simple Weber ratio does not take account of the response bias. We have made (15) detailed comparisons between the predictions of the analytical response functions obtained from the experiments reported here and a number of laboratory, simulator, and field results reported in the literature. In particular, we find that the results of Braunstein and Laugherty cited by Mortimer agree well with ours if one assumes that the percentage of erroneous responses they report correctly measures the response level the subjects were choosing. The results of Braunstein and Laugherty (as well as others) have embedded within them a response bias not only of the same sign as we observed but also of the same magnitude.

In the interests of brevity we have chosen in this paper to present our results only as a response to U/S, as opposed to the essentially equivalent ΔS/S interpretation favored by Mortimer. The quantity U/S appears as the stimulus in the most successful of the analytical car-following models, namely the reciprocal spacing model (16). Intuitively, this function implies that the subject senses relative speed directly, his judgment being scaled by a spacing factor.

The instrumentation that we used to measure vehicle trajectories is a very effective research tool and has been successfully and conveniently used since 1963 (17-22). Apart from the obvious advantage of no mechanical link between the cars, it offers a degree of flexibility and precision not obtainable with earlier devices. Spacing changes were measured to within 0.2 ft and speed to within 0.2 ft/sec in these experiments, and further development of this equipment since then has increased its precision.

The comments of Snider appear to stem from a misunderstanding of the goals, execution, and conclusions of the experiment we have described. The longitudinal control of a vehicle can be considered to require 3 distinct tasks from the driver. First there is perception, then decision, and finally execution of a control input. All these, as well as the mechanical response of the vehicle, are lumped together as one grand system response in car-following models. The overall driver-vehicle system lag, τ, has contributions from all these sources. Car-following models do not yield information on the separate processes of perception, decision, control input, and vehicular response. It was the purpose of the present study, as indicated by the title, to experimentally investigate the perceptual aspects of the problem, and only the perceptual aspects. Precise measurements on the perceptual process require isolating it from the other processes.

We reiterate that, if a subject is permitted to view an increasing stimulus and respond when he chooses to do so, what is measured is a function of both his perceptual sensitivity and his willingness to make a decision. Without prior knowledge of one of these, it is impossible to say anything about the other. Because sensitivity and willingness to decide are both involved in the measurements cited by Snider, they are characterized by large variance, as is apparent in the plot submitted by him. This variance is much greater than would permit discrimination between one interpretation or another, such as a response to vehicular pitch. For example, in Snider's graph (which is, incidentally, for his most consistent subject), at a spacing of 200 ft there is one response to spacing change of under 2 ft whereas in other cases there was no response until the spacing change had exceeded 25 ft. The variability at other spacings is similarly large. In general, when the standard deviation is considerably greater than the mean, it is very difficult, if not impossible, to distinguish the underlying process.

Our data do indeed imply that, if 2 cars traveling at 45 mph are about 300 ft apart, a driver in the following car will perceive at the 0.75 level after a 4-sec look that he is gaining on the lead car. There is no reason why the driver should decide to do anything as a result of this perception. If he is content with his current speed, he will continue to maintain it. If he desires to go faster he will catch up to the lead car and enter a car-following mode. We might stress that the experimental car-following work indicates that the lagged response is proportional to the stimulus for stimulus values well above threshold. There is no reason for supposing that there are very small responses to near-threshold stimuli. In fact, observations indicate that we should not expect such behavior.

We are at a loss to understand the nature of Snider's objections to our example. At a closure rate of 3 mph from a distance of 200 ft, the time to collision is over 45 sec—more than an order of magnitude greater than even the slowest motor response. Our conclusion was that limitations in the ability of an alert driver to detect the sign of relative motion were unlikely contributors to accidents. We did not state that other factors, such as inattention or vehicle response, do not contribute to accidents.

The technique we have used permits sufficiently clean and precise measurement of perceptual thresholds in car-following so that our results can be directly compared to laboratory-measured thresholds. When this is done the quantitative agreement (including spacing dependence and exposure time dependence) is sufficient to suggest the conclusion that a disc moving in a featureless environment simulates well the perceptual task in following a vehicle. The most prominent difference is that there is no response bias in the laboratory studies. It is our conjecture that the origin of the response bias arises from the subject's motion through his environment.

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