THE INFLUENCE OF MOTION AND AUDIO CUES ON DRIVER PERFORMANCE IN AN AUTOMOBILE SIMULATOR

by

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INTRODUCTION

The tremendous loss of lives and property attributable to motor vehicle accidents in the United States qualifies this hazard as one of the most serious confronting society today. In view of the scope and magnitude of this problem, considerable efforts have been made to reduce the number and severity of these events. Toward the achievement of these goals, countermeasures aimed at vehicle and roadway improvement are in use today and investigations concerning driver behavior are being conducted.

In view of the complexity of the driving task and the variability of the human being, studies concerning automobile-driver behavior involve a myriad of variables. In coping with the intricacies of such a problem, the experimental approach affords the investigator a very broad scope of inquiry as well as a selectivity and control of variables limited only by imagination, instrumentation technology, and economics. Within the experimental domain, driver oriented investigations are generally characterized as either direct or indirect. The latter involve the extrapolation, from non-driving oriented research, of results which are believed to be pertinent to the driving task. Examples of such indirect investigations are those dealing with visual acuity, depth perception, reaction times and those concerning certain aircraft-oriented control tasks (Bergeron, 1970; Shirley and Young, 1968; Young, 1967).

The direct approach more generally avoids the assumption of pertinence to the driving situation and consequently the results are more readily acceptable. Traditionally, research of this type is conducted by means of an instrumented vehicle in a real driving situation (full scale investigation) or by means of a laboratory driving simulation device (Schori, 1970).

The question of validity (with respect to applicability of results) regarding full-scale and simulator-type investigations, is the subject of much concern among researchers, but unfortunately, the object of very little published research. Both approaches (full-scale and simulation) have their proponents and their relative advantages and disadvantages, and are widely used in contemporary driver performance research.

In a practical sense, on the road or full scale investigations generally necessitate minimal equipment costs (car) although the cost of instrumentation can be very high. Experimental facilities such as parking lots, air fields or even public roads are generally adequate and readily available. Technically, the primary advantage of full-scale research is that the applicability and generality of results are less subject to skepticism than the findings of simulator-type research.

The basic disadvantages of the full-scale approach are the limitations concerning choice and control of variables and the repeatability of results.

Simulator-oriented research has certain advantages over the on the road method. As suggested by Fox (1960) and Stephens (1967), these advantages include: (a) increased safety in that hazardous real-life situations such as poor visibility or high speeds can be investigated; (b) expanded scope of inquiry which permits a systematic investigation of infrequent events such as accidents or emergency situations; (c) better experimental control over independent variables, maintained by eliminating or holding constant the effects of extraneous variables; and (d) reduction of experimental time by simulating conditions that occur only periodically in the real world such as dusk or rush-hour traffic.

Regardless of the experimental approach to driver performance investigations, consideration must be given to the reality that human behavior is almost always modified when examined in a test situation.

Further discussion will be limited to the subject of driving simulation, as it is toward this type of research that the present thesis is directed.

Driving Simulator Technology

Driving simulators, as the name implies, attempt to provide the human operator with the stimulus complex associated with the driving task. Generally some combination of visual, audio, motion, and somesthetic cues comprise the input to the operator. Simulators vary greatly with respect to the number, precision, and complexity of the stimuli which are presented. Categorically, the complexity and usually the realism of simulators are specified by the dichotomous labeling of whole or part-task simulator. Generally most (perhaps all, to date) simulators are of the part task variety in that they attempt to simulate only some portion of the total driving task.

Part task simulators exhibit a wide range of complexity with respect to that portion of the total driving task which they attempt to present. This range of complexity extends from very limited scope simulation concerned with only one measure such as accelerator to brake pedal response time, up to, but not including, the whole task simulator.

Two basic classifications concerning the visual display categorize most driving simulators. One classification specifies the type of visual display. Possibilities include television display, shadowgraph, motion picture projection, and direct viewing displays. The other basic categorization defines the visual display system as being either programmed (open-loop) or unprogrammed (closed-loop). In the case of the unprogrammed display presentation, the operator (driver) is continuously in control of the state of the vehicle (speed, position, direction, etc.) and, consequently receives real-time visual feedback much as he would in a real driving situation.

Programmed displays characteristically specify some particular route, lane position, speed, etc., and permit the driver only slight deviations from the programmed condition. As a result, meaningful and appropriate visual feedback to the driver is available only when he operates the simulated vehicle within the confines of the program. These two basic classifications are not mutually exclusive but certain combinations are precluded by technical limitations.

The driving simulator has demonstrated its utility in the research world and is very popular as a training device, as evidenced by its widespread use in public school driver education programs. Categorized by the type of visual display used, a brief description of various research-oriented driving simulators will be given under the headings of television, motion picture, point light source (shadowgraph), and direct viewing displays.

T.V. type displays. This type of simulator employs a television display directly or by projection onto a screen (Schmidt projector). The source of the projection image is generally one of three types: a static, three-dimensional scale terrain model; a moving-belt roadway model; or a computer type generation.

Located at the (no longer existent) U.S. Public Health Service Driving Research Laboratory (Providence, R.I.), a simulator built by Goodyear employed a large terrain model over which a gantry-mounted T.V. camera moved. Inputs by the driver (steering, accelerating, *etc*.) controlled the camera movements and consequently the image projected onto the driver's viewing screen. The driver viewed and controlled this image from a statically mounted automobile. (Barett, Kobayashi, and Fox, 1968; McKelvey, 1967).

A similar system is used at the simulator facility of the Institute of Transportation and Traffic Engineering, U.C.L.A. (Wier and Wojcik, 1972; Wojcik and Allen, 1971). Here the T.V. camera, viewing the terrain and controlled by the driver, has only two degrees of freedom: heading angle and lateral deviation. Forward motion is provided by a belt roadway which is slaved to a chassis dynamometer driven by a fixed automobile. The driver is seated in the automobile and views a projected T.V. image of the straight, belt roadway. Generally, simulators of the T.V./terrain type are most critically limited by the extent of their terrain model.

Using a Schmidt projection on a lenticular screen, the Cornell Aeronautical Laboratory simulator (Wierwille, Gagne, and Knight, 1967) electronically generates a geometric roadway composed of a solid centerline, two dotted sidelines, and roadside posts. Steering inputs by the driver simulated position and orientation changes by moving the roadway image in translation and rotation, respectively. A more recent version of this CAL simulator (Sugarman, Cozad and Zavala, 1973) employs rear projection with the Schmidt device, a Fresnel lens for image collimation and provides yaw and roll motion cues to the driver's platform.

In conjunction with the Swedish Traffic Safety Council, SAAB Motor Company has developed a simulator which visually displays a roadway image made up of 16 line segments. A program generator and analog computer create the roadway and fence post image which is projected from a cathode ray tube onto a translucent screen. The driver's platform moves from side to side relative to the display to give the visual sensation of lateral movement (Electronics, Nov. 1967).

Simulators using the computer generated type displays are generally quite versatile in their research applications providing that minute detail of the visual display is not essential for the particular research being undertaken.

Point light source display. Another class of simulators employ a point light source or shadowgraph display. One such simulator at the University of South Dakota (Ellinstad, Kimball, and Burgan, 1969) has four major components: an automobile (or mockup), a terrain model, a point light source which is directed through a transparent disk on which a driving environment is painted. The image is projected onto the rear of the translucent screen. The driver's controls (steering wheel, brake, etc.) control the rate and direction at which the driving environment passes in front of the light source and consequently govern his speed and direction of simulated travel.

As with the terrain/T.V. simulators, the shadowgraph simulator is constrained by the physical size of its terrain model. Further limitations exist in that the terrain model must move relative to the point light source.

Direct optical viewing. A simulator using this type display was developed by R.C.A. and used at the USPHS Driving Research Laboratory (Schori, 1970). A terrain model in which the road surface is a system of conveyer-type belts is viewed through a lens system and translucent screen by the operator. The speed of the belts determines the speed of the simulated vehicle and is controlled by the driver's accelerator pedal. Steering changes create lateral position changes for the automobile (or mockup) relative to the belts, thereby simulating a change of location on the road. It should be noted that, according to standard simulator nomenclature, despite this lateral mobility of the automobile, this simulator is of the fixed-base variety. The term moving base is applicable only to those simulators for which the purpose of the motion is to simulate inertial forces on the operator.

Generally simulators of this type have the potential for an extremely realistic but limited, visual display and are usually restricted to applications involving car following, passing, and straight-road tracking behavior.

Motion picture displays. The photographic medium used in displays of this type is relatively inexpensive, quite realistic, easily displayed and, as such, is very widely used (Beinke and Williams, 1968; Kobayashi and Matsunaga, 1964).

Usually,a motion picture taken from a moving car is projected onto a screen in front of, and sometimes also behind, an automobile. The simulator operator has a forward view of the moving roadway and generally (by rear view mirror or back window) a moving view of where he has been. Generally, speed changes can be accomplished by allowing the simulator driver to change the projection rate of the film through his accelerator movements. Steering maneuvers are generally limited, and are usually restricted to only slight changes in heading. Such changes are created by coordinating steering wheel movements with the pan rate of the projector. Lane changes are permitted only when the original picture taking vehicle has executed such a maneuver, in which case the simulated display will make this change even without compliance by the simulator driver. As with most of the other types of simulators, many variations exist concerning the existence of motion, vibration and sound cues, the realism of the feel and response of the controls, etc. Often however, there is a dearth of these extra cues.

Although very popular, this type of display system, because of its extremely programmed nature, provides less flexibility than any of the above mentioned approaches.

Purpose

Published research involving driving simulation is generally of an applied nature and reflects the use of simulation as a tool which enables the researcher to study certain aspects of the driver, the vehicle, or the roadway under laboratory conditions. In addition to the nature of the particular driving task to be investigated, monetary constraints often dictate what physical attributes of the driving task are to be included in the simulation. Apparently, the high cost of incorporating physical motion exerts formidable influence on simulator design as most are of the fixed-base variety.

As illustrated by the above descriptions of driving simulators, much variation exists regarding the visual display techniques they employ and the number and nature of physical motions they incorporate. However, the available literature is apparently devoid of information regarding the criterion involved in matching pertinent aspects of the driving task with necessary attributes of the simulator. Especially, with regard to motion cues, many questions concerning subjective realism and objective validity are apparently unanswered. It is intuitive that certain questions of the following nature should be answered prior to the design of a simulator and consequently before the results of any applied research can be accurately interpreted. These questions include:

a) Is physical motion necessary in simulation?

b) What motion cues should be presented?

c) To what extent is driver performance influenced by the deletion of any given cue?

Similar questions regarding sound and vibration are also pertinent.

Until such questions can be objectively answered, design criteria regarding motion, sound, vibration, etc. for driving simulators will remain somewhat ambiguous, subject to the reseacher's fancy (or budget), and to some degree, scientifically unfounded.

It is the intent of this research to provide information that is pertinent to, and supportive of, the establishment of design criteria for automobile driving simulators. Pursuant to answers to the above questions, this research investigates the effects on driver performance of certain motion and audio cues.

It is felt that the information generated in this investigation would be beneficial to those concerned with designing a simulation device which would provide maximum realism within budgetary constraints or equipment limitations.

LITERATURE REVIEW

Little, if any, of the published research on the subject of driving simulators is directed toward the investigation of simulator characteristics as independent variables. Consequently, no direct research was reviewed which appeared pertinent to the present, apparently unique, investigation.

However, from an indirect point of view, the work of Young (1967) appears pertinent to the driving situation by virtue of the task similarities. Young's experiments used a moving-base simulator programmed to simulate various flight configurations. Results involving a single-axis tracking task showed that moving-base simulation yields better agreement with flight experience than fixed-base simulation. For most applications, the simulation of angular motions was shown to be more beneficial than were the translational motion cues.

Bergeron (1970) conducted experiments with a two-axis simulator in which compensatory tracking tasks were performed. Although no significant differences were observed in the single-axis tests, the two-axis motion tests (pitch and yaw, and pitch and roll) showed significant differences in the tracking errors for the motion/ no motion comparison. A decrease in normalized tracking error was observed when motion was added.

Concerned only with roll motion cues, Shirley and Young (1968) investigated the human operator's use of the above in a compensatory tracking task with a random disturbance input. The results suggest that the addition of roll motion cues to the visual cues is beneficial to operator performance for conditions in which human operator lead is greater than three radians/second.

An investigation by Matheny, Dougherty and Willis (1963) showed that the addition of motion cues was significant enough to change the results of an interpretation task comparing outside-in and inside-out displays. The results also indicated that the degree to which angular motion is duplicated is most important.

In a synopsis of training device design, Kinkade and Wheaton (1972) suggest that "... motion cues will contribute to improved control of the vehicle in situations where visual information is degraded or inadequate." In general, they state that the actual benefits of simulated motion depend on the degree and kind of response to motion cues demanded by the task.

METHOD

The Simulator

The driving simulator used for this research was designed and built at Virginia Polytechnic Institute and State University under the sponsorship of the General Motors Corporation and the University.

The simulator provides the operator with an unprogrammed television-type display in coordination with the motions of yaw, roll, and lateral translation. Two channels of sound along with vibration are also provided. A more complete description of the visual, motion and audio systems follows. (See also Wierwille, 1973) Figure 1 contains the block diagram of the simulator, while Figure 2 illustrates the physical placement of the key simulator elements. Photographs of the motion platform and experimental layout appear in Figures 3A and 3B.

Visual system. Generation of the simulated roadway image is accomplished by hybrid computer (EAI-380). Computer-generated signals are initially displayed on the 4 x 5 in. face of a cathode ray tube (Tektronics 604). A T.V. camera (Dage RGS-50) scan converts this image and transmits it by cable to a 23 in. (diagonal) T.V. monitor (Setchell-Carlson 3M912) mounted above and behind the dash on the upper motion platform. A Fresnel lens (Edmund Scientific, 19 1/4" x 24 3/4") with an effective focal length of 20 in., located between the monitor and the human operator, decreases the roadway image proximity to the driver and enhances the illusion of distance (effective distance 33 ft.). Additional realism is provided by a 1/8 in. plexiglass

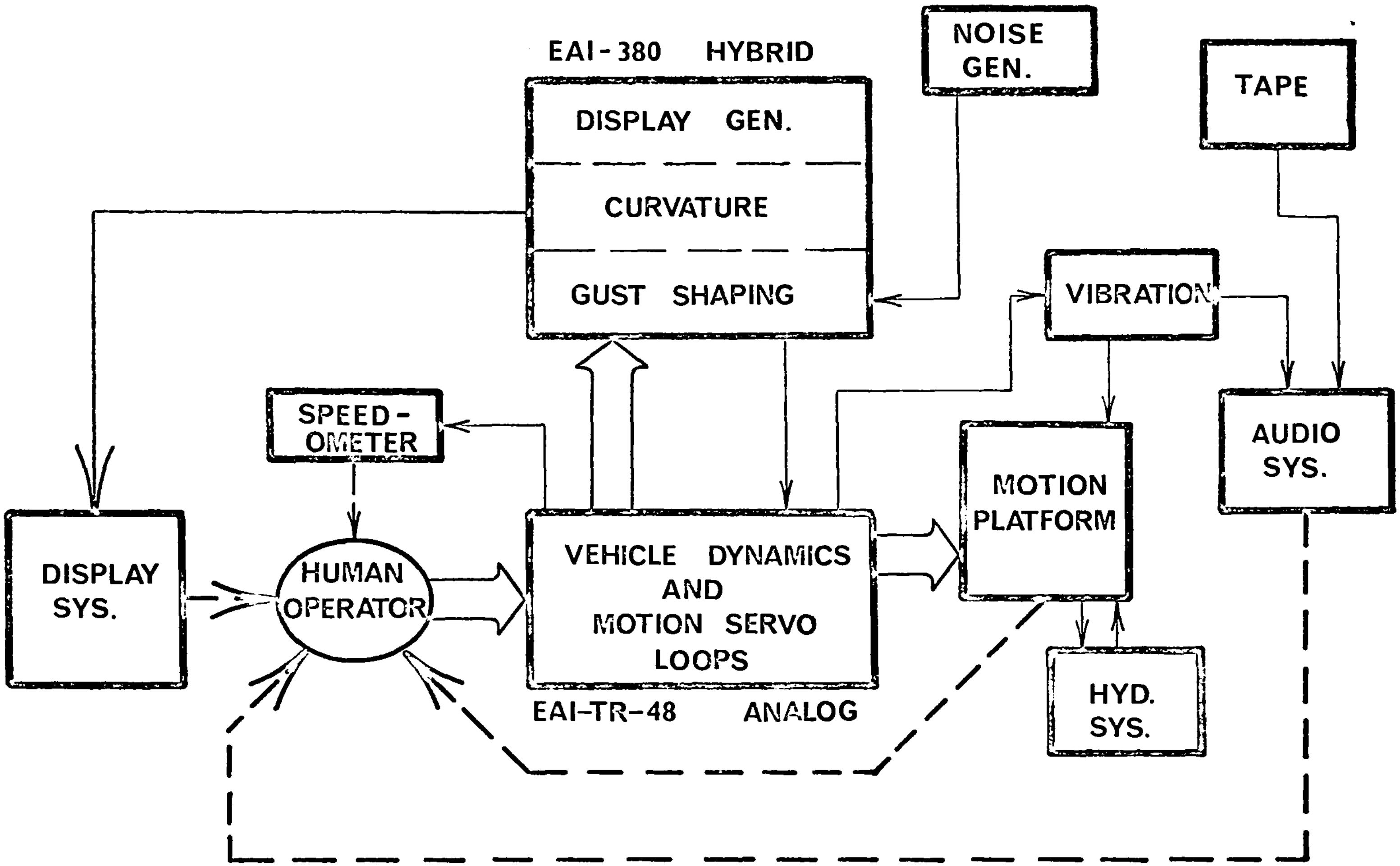

Figure 1. Block diagram of driving simulator.

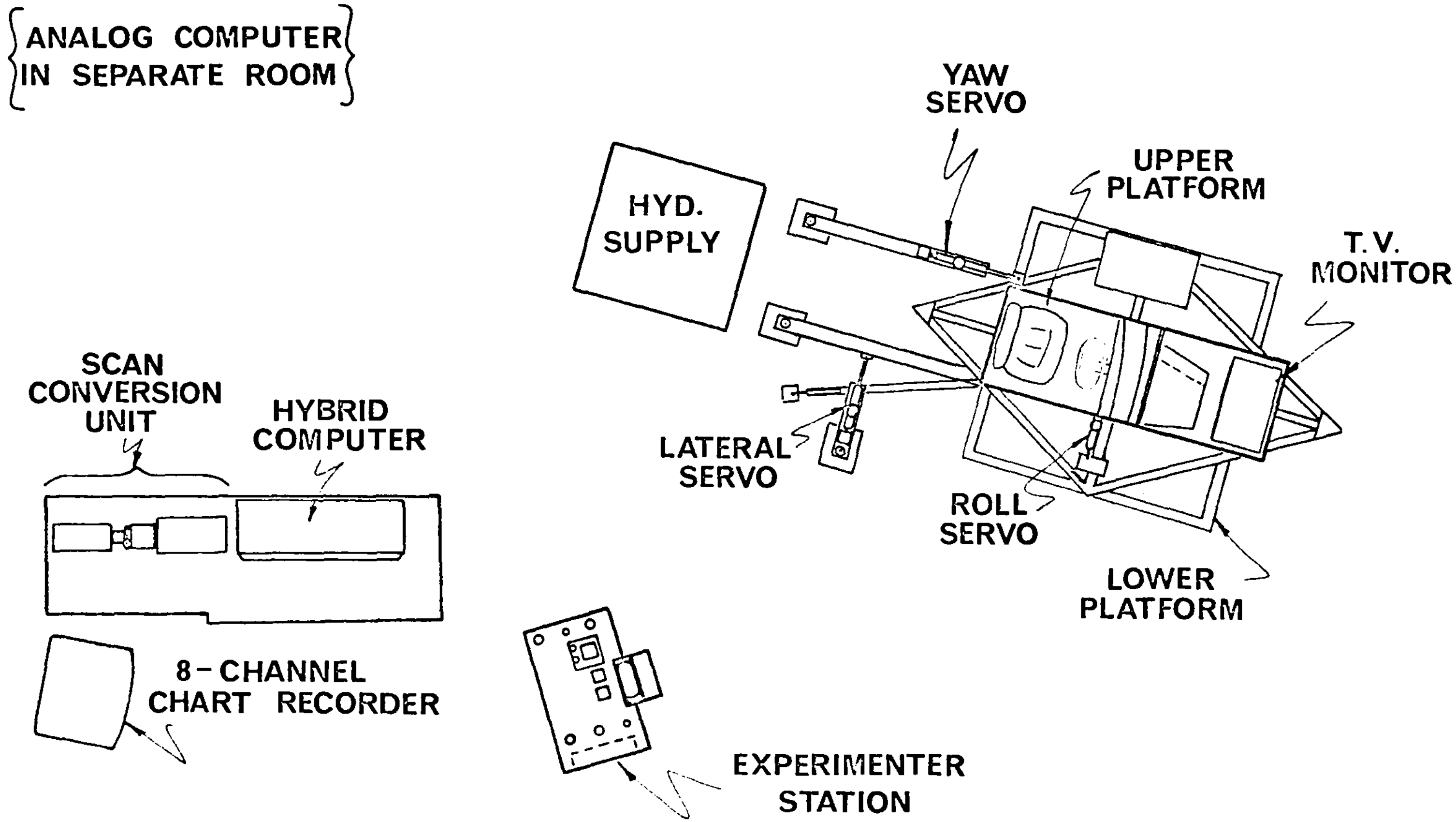

Figure 2. Layout of key simulator components.

Figure 3A. Driving simulator motion platform.

Figure 3B. Driving simulation facility with operational personnel.

windshield and a sheet-metal mock-up representing a hood and fenders immediately in front of the dash. The field of view provided by the T.V. monitor and lens subtends 39° vertically and 48° horizontally.

During simulation all room lights are turned off so that only the T.V. display and the illuminated speedometer are visable to the driver. An 11 in. (diagonal) closed circuit T.V. monitor providing the same roadway display (excluding Fresnel lens, hood, and windshield) is located on the experimenter's console. Figure 4 indicates the arrangement of the display equipment on the upper motion platform. An operator's-eye view of the roadway image is shown in Figure 5. It should be noted that the actual image is considerably sharper than indicated by the photograph of Figure 5 because the illumination levels required camera shutter speeds which were unable to completely freeze the moving image.

Motion system. Motive power for the motion platform is provided by an electrically driven hydraulic pump whose regulated output delivers fluid of from 900 to 1100 P.S.I. to the system. Acoustical insulation of the pump unit controls the noise level from it in the simulator room. A triple-bank shut off valve enables the experimenter to select an operative/inoperative mode for each hydraulic servo.

Structurally,the simulator is composed of an upper and a lower platform, three main struts, and three motion servos.

The upper platform consists of a standard automotive configuration including bucket seat, dashboard (with speedometer), steering wheel, brake and accelerator pedal, and the visual display equipment

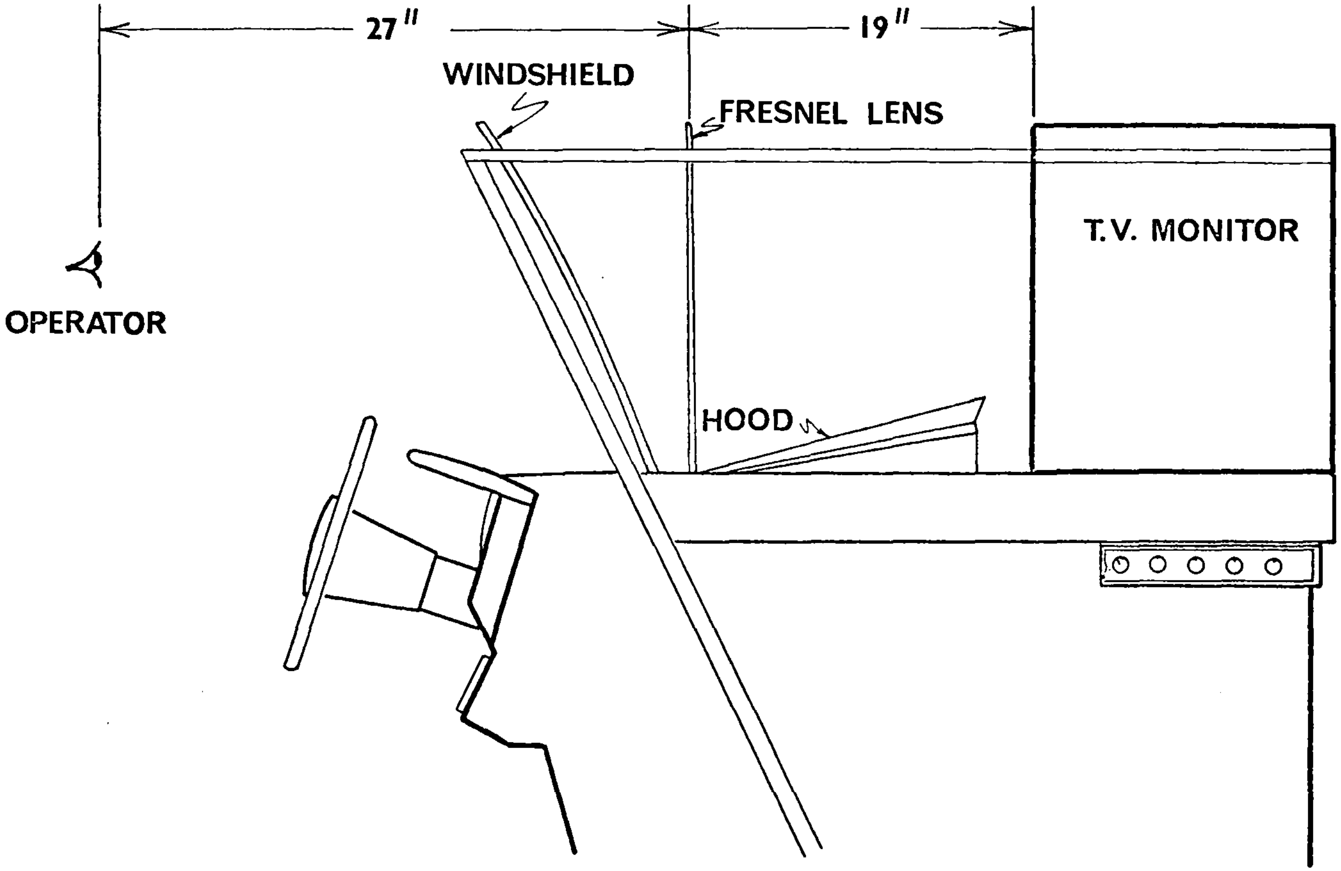

Figure 4. Arrangement of visual display equipment on upper platform.

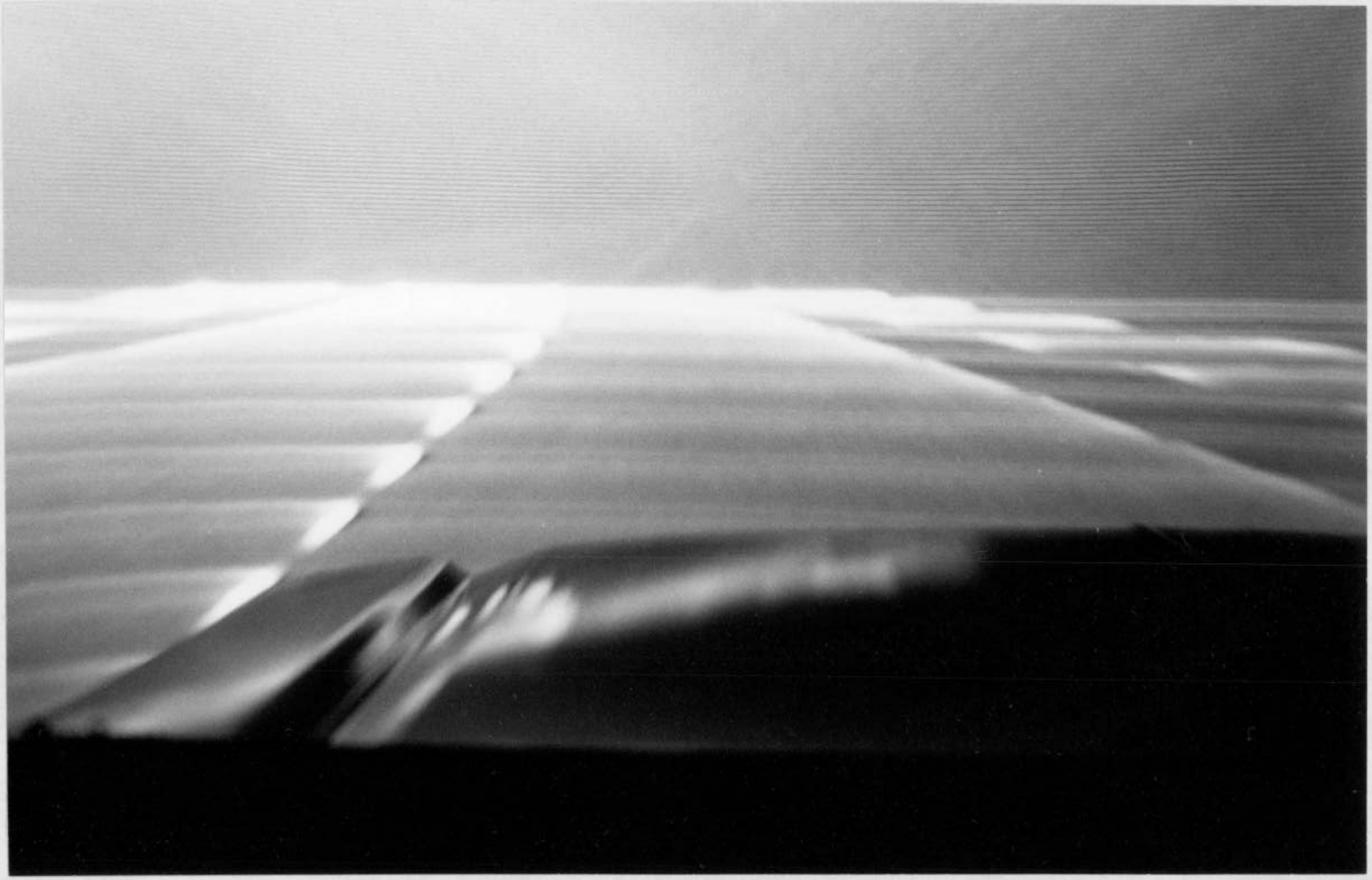

Figure 5. Photograph of roadway image.

described above. The upper platform is pivoted at each end which permits roll motion about an axis 13 in. from the upper platform floor. The roll motion is accomplished by the roll servo which is attached to both the upper and lower platforms.

The lower platform, while providing support for the upper platform, is supported by 9 precision rubber-wheeled casters, which enable the platforms to move freely in yaw and lateral translation. One fixed-length strut and two servo operated struts, all of which have one end pivoting on a floor mounted support, provide the platforms with the yaw and lateral translation motions.

Each motion servo is controlled by its own electro-mechanical valve and monitored by its respective feedback potentiometer which receives signal inputs from the analog computer.

Simulation of vehicle dynamics is controlled by analog computer (EAI TR-48). Driver inputs to the steering wheel and accelerator pedal are sensed by potentiometers and converted to electrical analog signals. These signals form the input to the equations of motion simulated on the computer. The outputs of these equations of motion consist of analog voltages of vehicle roll, yaw, and lateral position, which form the signals to be applied to the motion servos. These signals are applied to the driver's speedometer and also to the image generation computer, which continuously adjusts the visual display characteristics (position, perspective, speed, etc.) to correspond to the simulated vehicle state.

<u>Audio system</u>. To enhance the realism of the simulation as well as to mask any residual noise created by the hydraulic pump , two channels of

sound are provided. Channel one simulates the aerodynamic and chassis/ road sounds of highway driving. The source for this portion of the simulation is a pre-recorded tape played through a stereo tape deck (Sony 270) by a pair of speakers. One is located directly behind the driver's seat and the other at the front of the lower platform.

The other sound channel is velocity dependent (in freqency and intensity) and, as such, represents the sound associated with engine and drive train. A small electric motor fitted with an eccentric weight and located in the lower firewall area, provides velocity dependent mechanical vibration to the platform and serves as the sound generator for channel two. Two small magnets located diametrically opposite each other on the eccentric weight pass by a pick-up coil disturbing the field of the coil in a velocity dependent manner. The signal picked up by the coil is processed by a shaping network and amplified by the monitor mode of the stereo tape deck. Presentation of the channel two sound is by the speaker enclosure located at the right front of the lower platform.

Experimental Design

The primary concern of this research is the investigation of the influence on driver performance of certain motion and audio cues. Inherent in the capability of the simulator were three separate motion cues - roll, yaw, and lateral translation - and any of their combinations. Also available were two channels of sound - roadway sound and engine noise (including platform vibration) - and the visual display of roadway and speedometer. In the interest of experimental design simplicity, meaningfulness,and overall time practicality, it was decided that a total of six experimental combinations of these available cues would be evaluated. The six combinations (hereafter referred to as experimental conditions) are explained by Table 1.

Consideration was given to learning effects and the possibility that a subject might synthesize a selected cue if subjected to a missing cue condition after having driven under the control condition. In the interest of obtaining unbiased driver reactions to the various experimental conditions, the experiment was designed to provide each subject with only one experimental condition. As a trade off between statistical power and procedural practicality it was decided that eight different subjects would be randomly selected for each of the six experimental conditions (total of 48 subjects).

To minimize learning effects, subjects were given a practice period of sufficient length to allow the driver a comfortable feeling with regard to simulator control, display,and feedback dynamics.

Procedure

Eight different student volunteer subjects, ranging in age from 19 to 30 years, were assigned to each of the six experimental groups. Assignment was random with the exception that exactly two subjects per experimental group were female. Subjects were paid for their participation in the experiment.

Each subject, upon arrival, was asked to read a set of general

TABLE 1

Tabular Description of the Six Experimental Conditions with Respect to Motion and Audio Cues

Experimental Condition	Cues: Motion			Cues: Audio
	Roll	Yaw	Lateral Trans.	Engine Noise
Control	Yes	Yes	Yes	Yes
No Roll	No	Yes	Yes	Yes
No Yaw	Yes	No	Yes	Yes
No Lateral Trans.	Yes	Yes	No	Yes
No Motion	No	No	No	Yes
No Engine Noise	Yes	Yes	Yes	No

"Yes" indicates presence of the cue
"No" indicates absence of the cue

instructions (Appendix A), after which questions concerning the written instructions only were answered by the experimenter. The subject was then seated in the simulator and verbal instructions concerning the operation of the controls (emergency motion button, steering wheel and accelerator pedal) and reading of the speedometer were given. Subjects were informed that they would be given a 5-minute practice run, during which they were to get the feel of the simulator by practicing the maneuvers (lane changing and speed changing) mentioned in the instructions. Room lights were turned off, a communication check between subject and experimenter was made, and the simulator was activated by the experimenter. The motion/audio cue condition of the simulator during the practice run was identical to the condition to be used in the experimental data run.

During the 5-minute practice run, the subject was informed of and experienced straight road without gust (1 minute), roadway curvature without gust (2 minutes), straight road with simulated lateral and longitudinal wind gusts (1 minute), and the combination of both gust and curvature (1 minute). At the end of the practice run the simulator was stopped, the room lights were turned on, and the subject was instructed to take a 4-5 minute break in the adjoining hallway after which he would return for the data run. After the break, seating and start-up procedures were the same as before the practice run.

Experimenter and subject were in voice contact via intercom (speakers located on experimenter's console and operator's dashboard) throughout the experiment. To begin the experimental data run, the simulator was put into operation and the experimenter gave the first instruction: "Drive in the right-hand lane at 60 M.P.H." Table 2

TABLE 2

Schedule of Driver's Instructions and Gust/Curvature Conditions for Experimental Data Run

Time Min.	Time Sec.	Instruction	Condition Gust	Condition Curvature
00	00	Drive in right lane at 60 M.P.H.		
	15	Drive at 45 M.P.H.		
	30	Drive at 75 M.P.H.		
	45	Drive at 50 M.P.H.		
1	00	Drive at 60 M.P.H.	▮▮▮	
1	15	Drive at 45 M.P.H.	▮▮▮	
1	30	Drive at 75 M.P.H.	▮▮▮	
1	45	Drive at 50 M.P.H.	▮▮▮	
2	00	Drive at 70 M.P.H. for rest of run.	▮▮▮	
3	00		▮▮▮	▮▮▮
4	00			▮▮▮
5	00	Move into the left-hand lane.		
5	15	Return to the right-hand lane.		
5	30	Move quickly into the left lane and quickly return to the right lane.		
6	00	Move into the left-hand lane.	▮▮▮	
6	15	Return to the right-hand lane.	▮▮▮	
6	30	Move quickly into the left lane and quickly return to the right lane.	▮▮▮	
7	00	Move into the left-hand lane.	▮▮▮	▮▮▮
7	15	Return to the right-hand lane.	▮▮▮	▮▮▮
7	30	Move quickly into the left lane and quickly return to the right lane.	▮▮▮	▮▮▮

TABLE 2 (Continued)

Time	Instruction	Gust	Curvature
8 00	Move into the left-hand lane.		
8 15	Return to the right-hand lane.		
8 30	Move quickly into the left lane and quickly return to the right lane.		
9 00	Remove foot from accelerator and allow the vehicle to coast down to 30 M.P.H.		

gives the time schedule, gust/curvature conditions, and verbal instructions for the experimental run. As shown in Table 2, the 9-minute data run was composed of 9 1-minute blocks, each characterized by a certain task and a specific gust/curvature condition. The first two blocks required the driver to make instructed speed changes. The next three blocks involved maintaining a right lane position and a speed of 70 M.P.H. Each of the last four blocks required the driver to make instructed lane change maneuvers while maintaining a 70 M.P.H. speed.

Data Collection

The Data. A Sanborn (model 350) chart recorder was used to collect the data for this research. The recorder's 8-channel capacity was allocated as follows:

Channel 1 (Steering Wheel Position). Input to this channel was provided by a potentiometer located on the forward end of the steering column. A continuous indication of steering wheel position was obtained.

Channel 2 (Accelerator Pedal Position). The voltage output of a potentiometer attached to the pedal linkage provided an input signal corresponding to accelerator pedal position.

Channel 3 (Lateral Gust). A random noise generator provided input to a shaping network, the output of which was applied to the lateral servo control circuit and to the visual display generating system. This shaped, random noise, as seen and felt by the operator, simulated lateral wind gusts of low to moderate magnitude.

Channel 4 (Roadway Curvature and Longitudinal Gust). A programmed roadway curvature routine was accessible from the hybrid computer. The program created on the visual display the illusion of roadway curves with radii of curvature of from .25 to 1.0 mile. The program consisted of two consecutive 60-second routines. The sequence and magnitudes of curvature were exactly the same for each except that the directions (right- and left-hand curves) were reversed. The signal recorded on this channel was an output provided by the hybrid computer and corresponded to the radius of curvature being created on the visual display. Superimposed on this plot was another signal representing the magnitude of simulated longitudinal wind gusts. Generated and shaped like the lateral gusts, this noise was fed into the visual display control system and experienced by the driver visually as a change in apparent velocity, both on the T.V. monitor and the illuminated speedometer.

Channel 5 (Roll Position). A potentiometer located between, and monitoring the relative motion of, the upper and lower platform provided input for this channel. This signal corresponded to simulated vehicle roll position.

Channel 6 (Yaw Deviation). The analog computer provided an error signal corresponding to the algebraic difference of nominal straight-ahead and the longitudinal axis of the simulated vehicle. In the event of roadway curvature, nominal straight ahead was assumed to be in the direction of a tangent to the curve at that point. This error signal provided a continuous indication of yaw deviation.

Channel 7 (Lateral Deviation). The input for this channel was a signal, produced in the analog computer, describing the lateral deviation of the simulated vehicle from a nominal position.

Channel 8 (Velocity). The input to this channel was derived from the analog computer, where vehicle dynamics equations are being continuously solved. This state variable corresponded to simulated vehicle velocity and had the same value as that indicated on the dashboard speedometer.

Figure 6 shows a photo-reduced example of the eight data channels taken from an actual experimental run.

Data Reduction

Inasmuch as each of the nine blocks comprising an experimental data run was characterized by a specific gust/curvature condition, the indication of these conditions (Channels 3 and 4), rather than elapsed time, served to define block boundaries for the purpose of data extraction from the chart recordings. Although the different tasks that these blocks represented were not of interest as independent variables, all data were extracted from the records on a block-by-block basis. This procedure was used because these groupings might provide a format useful for future comparisons and also because the incremental time involved in this approach was considered insignificant. It will be shown that a per-block evaluation of the data was desirable for yaw and lateral deviation measures.

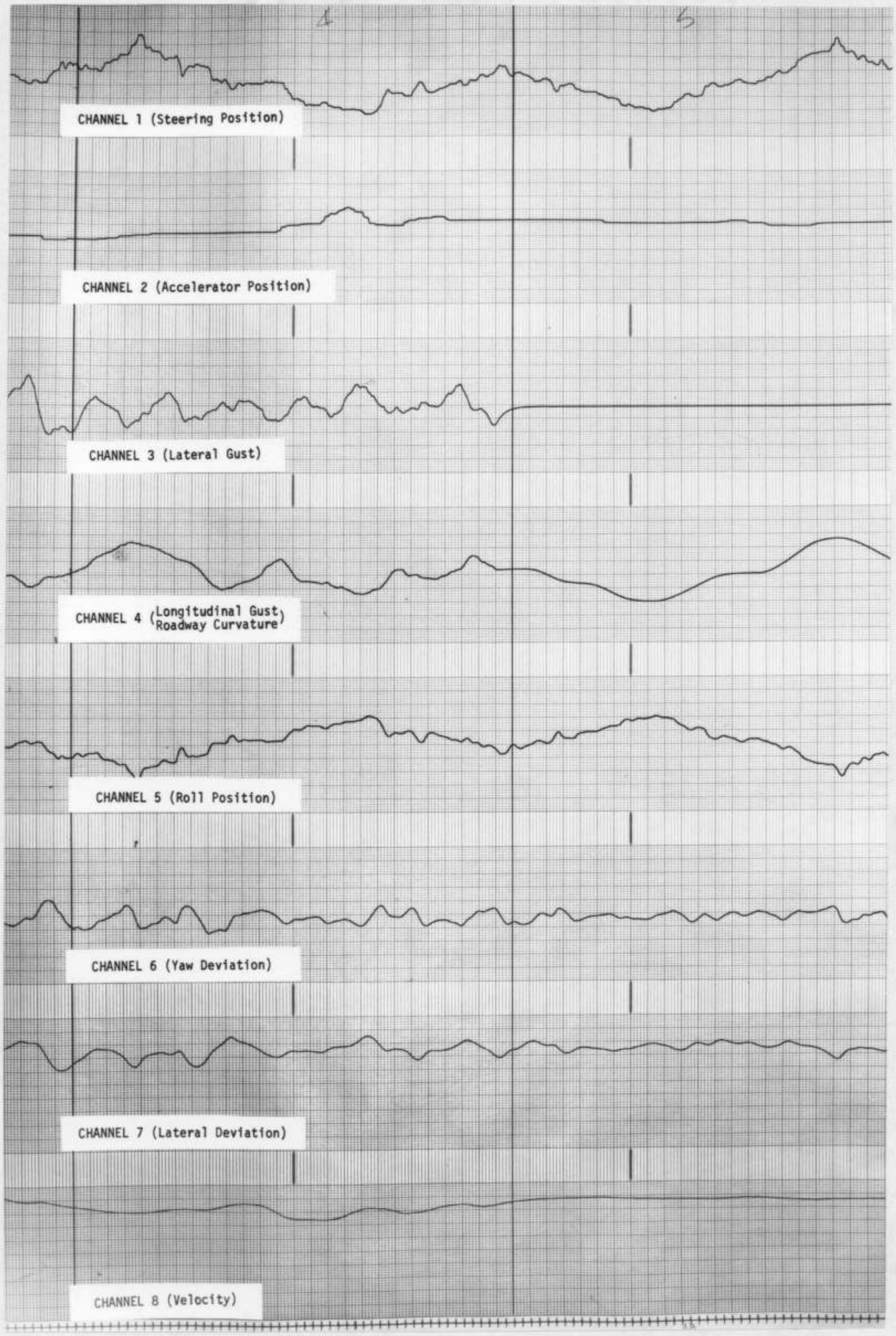

Figure 6. Photo-reduced example of the 8-channel chart recording.

The positional data of channels one and two were used to provide a reversal rate measure for steering wheel and accelerator pedal, respectively. The criteria for reversals was set at one chart division which corresponded to 3.4 arc degrees of steering angle and 3% of full pedal depression, respectively.

Yaw and lateral deviation measures were made for blocks one through five only because no lane change maneuvers were required for these blocks. It was felt that individual differences in lane changing techniques would introduce unmeasurable variations in the deviation data. In analyzing the yaw and lateral channels, data were sampled every second and a record was made of the distance from an arbitrarily established base line. For each channel a mean and standard deviation were computed. The computed standard deviation for each block was taken as the measure of yaw deviation or lateral deviation for that block.

The velocity channel (no.8) was evaluated for blocks three through nine only, as blocks one and two involved instructed speed change maneuvers. Again, it was felt that individual speed changing techniques would introduce undesirable variation in the velocity deviation measure. For the blocks measured, the instructed speed was 70 M.P.H. The standard deviation measure was made with respect to 70 M.P.H. instead of the mean speed; however, a mean was also determined.

Thus,the final product of the data reduction effort yielded, for each subject, the following performance measures:

1. The number of steering wheel reversals (greater than 3.4 deg.) over a 9-minute period.
2. The number of accelerator pedal reversals (greater than 3%) over a 9-minute period.
3. An average, over the first 5 1-minute blocks, of the deviation from a nominal straight-ahead orientation of the simulated vehicle (measured in degrees).
4. An average, over the first 5 1-minute blocks of the deviation from the mean lateral roadway position of the simulated vehicle (measured in feet).
5. An average, over the last 7 1-minute blocks of the deviation from the instructed 70 M.P.H. of the simulated vehicle (measured in M.P.H.).

RESULTS

The five performance measures, derived from nine minutes of continuous data, generated by each of 48 subjects provided the basis for the following analyses. A summary of the five performance measures, by experimental conditions, is presented in Appendix B. (It should be noted that the yaw and lateral deviation measures are expressed in arbitary units.)

Six Experimental Conditions

Initially, these data are analyzed, one performance measure at a time, as the influence of the six experimental conditions is investigated. Table 3 contains a summary of statistical test results for the five performance measures over six experimental conditions.

Steering reversals. The histogram of Figure 7 shows the effect of the six experimental conditions on the steering reversal measure. Each bar represents the average number of reversals for eight subjects. The average number of steering reversals (for nine minutes) ranged from 247 (no-motion condition) to 340 (no-engine noise). Relative to the control condition average of 328, these measures represent differences of -24.7% and +3.7%, respectively. In view of the nature of the reversal data (frequency count), the group totals (for each of the six experimental conditions) were subjected to a Chi-square test which revealed a significant difference ($p < .001$) among the six totals. Using Chi-square, a comparison of the control total with each of the five experimental condition totals revealed a significant difference for all but the no engine noise condition (Table 3).

Accelerator reversals. The six experimental group means of

TABLE 3

Summary of Statistical Test Results of Five Performance Measures over Six Experimental Conditions

PERFORMANCE MEASURE	STATISTICAL TEST: ANOVA	Dunnett control vs :	Chi-square: Overall	Control compared with : No Roll	No Yaw	No Lat.	No Motion	No Eng. Noise
Steering Reversals			178.5 ($p<.001$)	47.8 ($p<.001$)	94.2 ($p<.001$)	47.3 ($p<.001$)	160.7 ($p<.001$)	3.82 (N.S.)
Accelerator Reversals			38.0 ($p<.001$)	18.6 ($p<.001$)	9.67 ($p<.01$)	5.94 ($p<.02$)	.80 (N.S.)	16.54 ($p<.001$)
Yaw Deviation	F=4.756 ($p<.001$)	t=3.374 ($p<.001$) NO Motion						
Lateral Deviation	F=3.585 ($p<.01$)	t=2.969 ($p<.025$) No Motion						
Velocity Deviation	F=2.533 ($p<.05$)	(N.S.)						

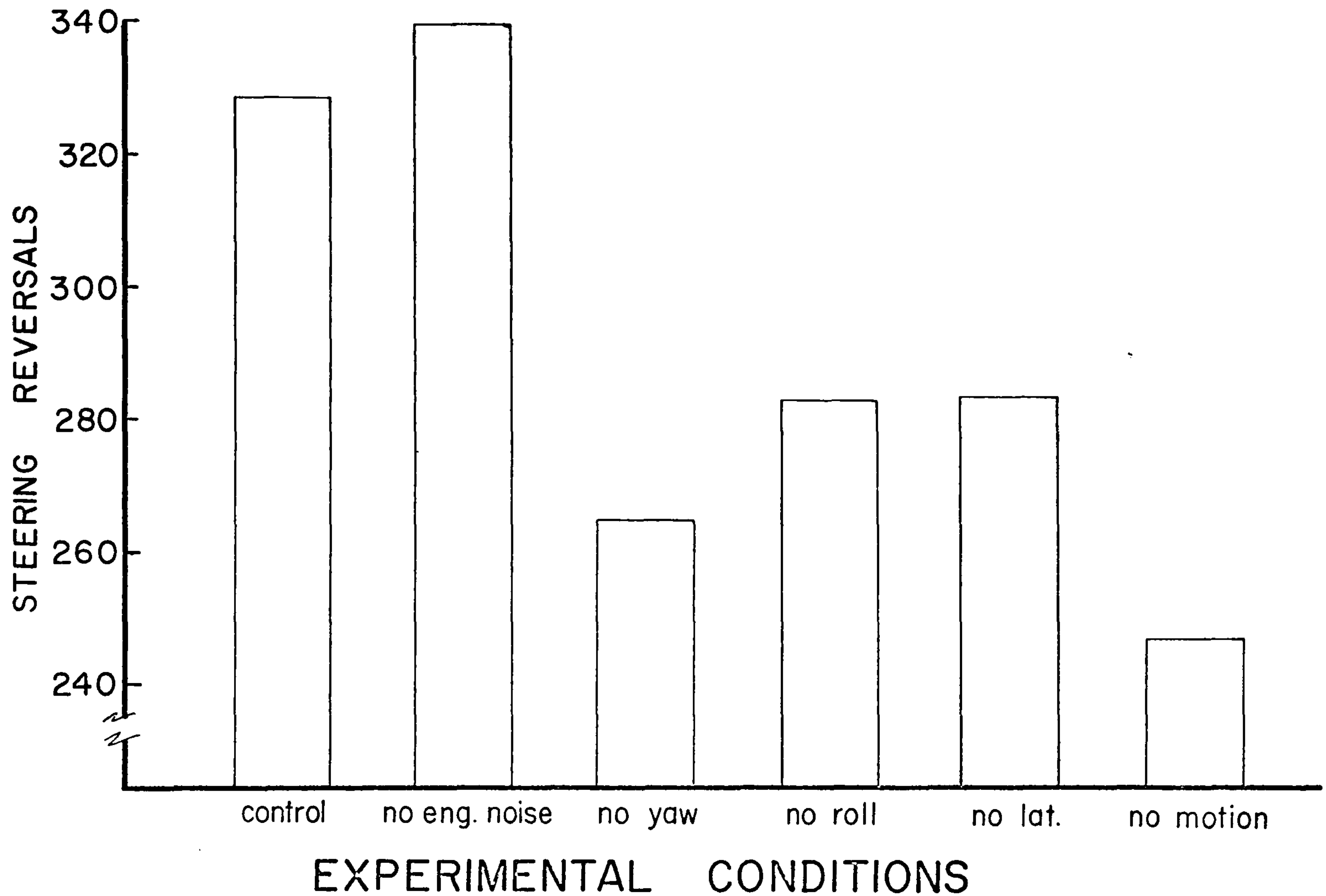

Figure 7. Histogram of steering reversals over six experimental conditions.

accelerator reversals are shown in Figure 8. The control group mean was 56.7 reversals with the lowest mean (49.8, No Lat. Trans) being 12.2% less and the highest mean (68.1, No Roll) 20.1% greater. A Chi-square test revealed a significant difference ($p < .001$) among the experimental group totals. A significant difference was shown (by Chi-square) between the control total and each of the remaining five totals with the exception of the no-motion case (Table 3).

Yaw deviation. The six group means of yaw deviation are shown in Figure 9. The no-motion group mean (.52 deg) showed the greatest difference (+33.3%) from the control group measure (.39 deg) while the no lateral translation group mean (.36 deg) was 7.9% less.

A one-way analysis of variance (Table 4) revealed a significant difference ($p < .001$) among the six group means. The no-motion group mean was shown to be significantly different from the control group mean (Dunnett's $t = 3.374$, $p < .001$).

Lateral deviation. Experimental-group means shown in Figure 10 varied from .36 ft. (No Lat.) to .54 ft. (No Motion) representing -8.7% and +33.7% differences, respectively from the control-group mean of .40 ft. A significant differenct ($p < .001$) among these group means was demonstrated by analysis of variance (Table 5). The no-motion mean was shown to be significantly different from the control mean by Dunnett's Test ($t = 2.969$, $p < .025$).

It should be noted that the measures of yaw and lateral deviation are physically related in that lateral deviation is approximately proportional to the integral (over time) of yaw deviation.

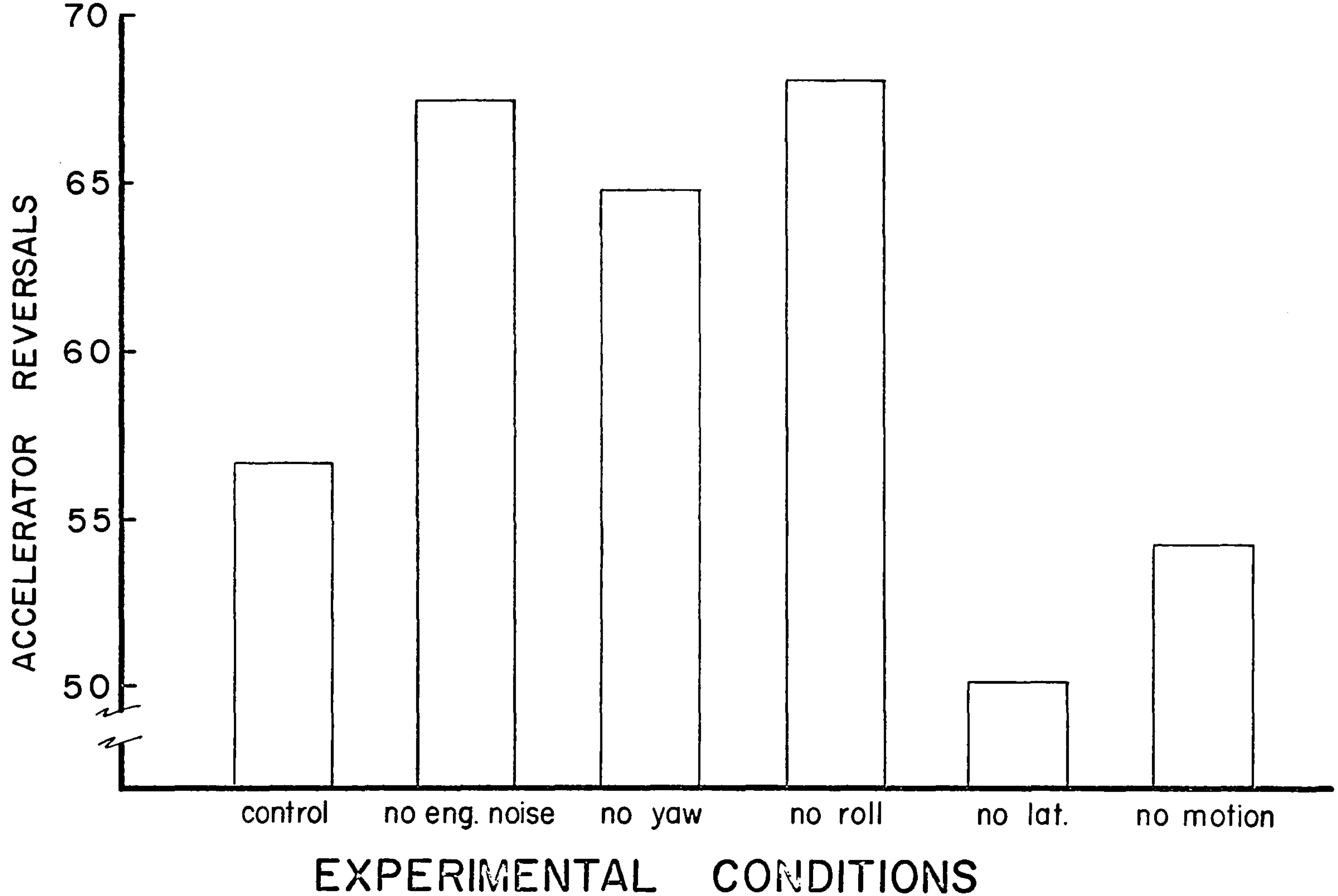

Figure 8. Histogram of accelerator reversals over six experimental conditions.

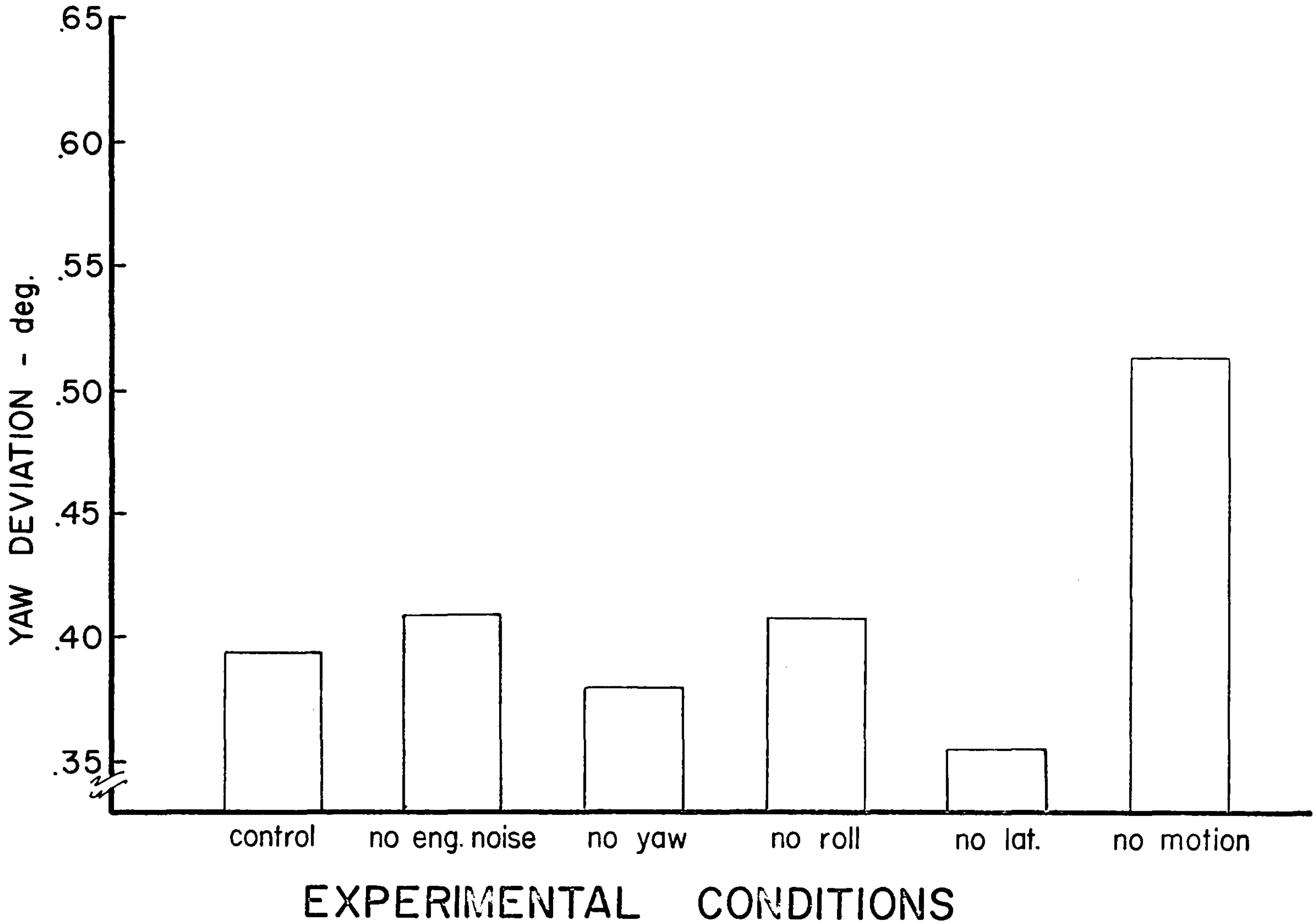

Figure 9. Histogram of yaw deviation over six experimental conditions.

TABLE 4

Analysis of Variance of Yaw Deviation over Six Experimental Conditions

Source of Variance	df	SS	MS	F
Experimental Conditions	5	.1068	.0214	4.756*
S/Exp. Conditions	42	.1908	.0045	
Total	47			

* $p < .001$

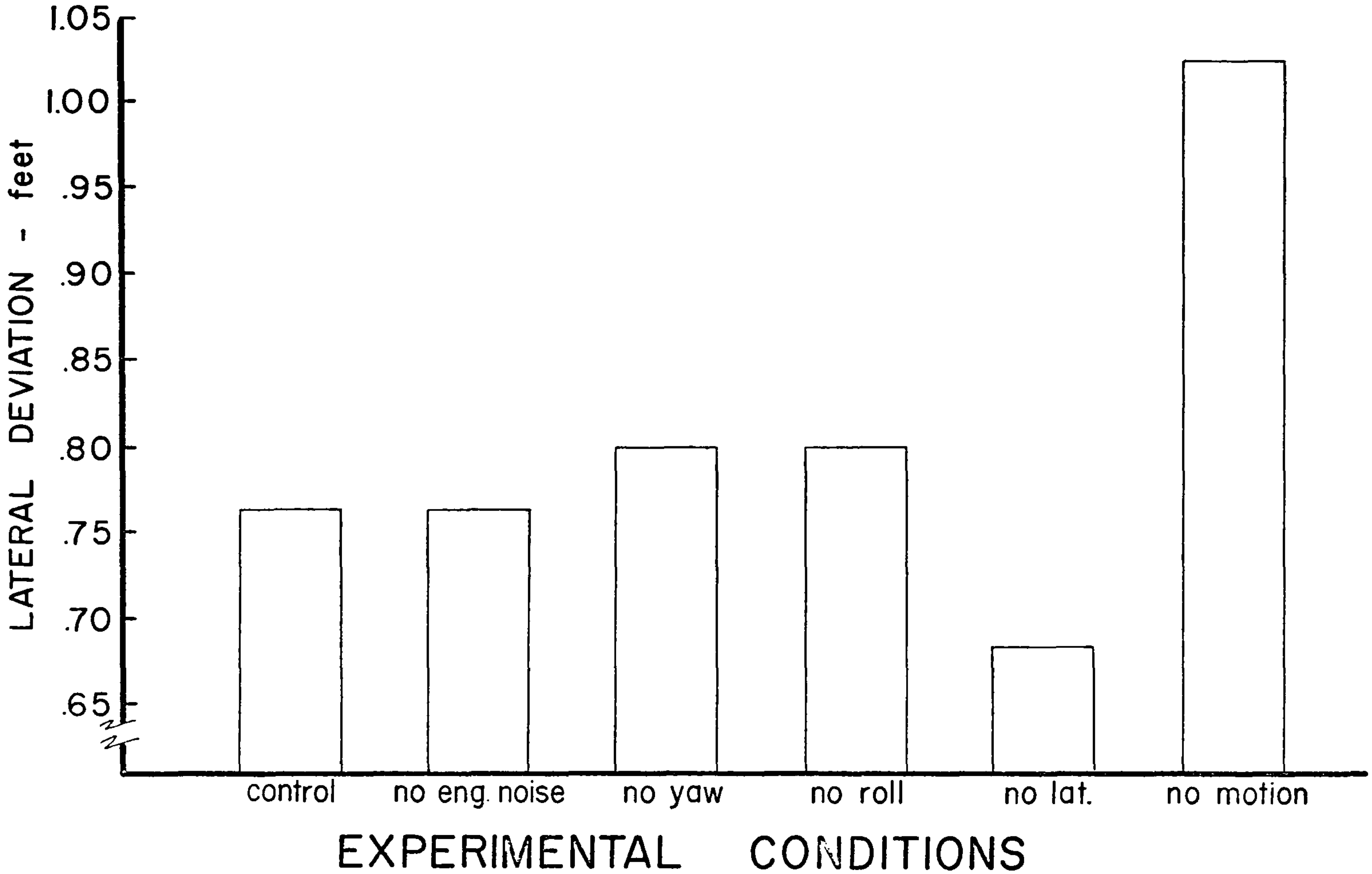

Figure 10. Histogram of lateral deviation over six experimental conditions.

TABLE 5

Analysis of Variance of Lateral Deviation over Six Experimental Conditions

Source of Variance	df	SS	MS	F
Experimental Conditions	5	.147	.0294	3.585 *
S/Exp. Conditions	42	.344	.0082	
Total	47			

* $p < .01$

Velocity deviation. As per Figure 11, the no-engine-noise group showed the largest velocity deviation measure (6.73 M.P.H.) while the no roll group had the smallest mean (4.29 M.P.H.). These results represented differences from the control mean (5.21 M.P.H.) of +27.2% and -17.7%, respectively. Although the analysis of variance (Table 6) showed a significant difference ($p < .05$) among the group means, no mean differed significantly from the control mean according to the results of Dunnett's Test.

As a summary, Table 7 presents, for each of the five performance measures, the percentage difference of each of the five experimental conditions from the control. Pursuant to a composite indicator of the influence, on driver performance, of these five experimental conditions, the right-hand column represents the sum of the absolute value of each of the percentage differences for each experimental condition. Although the no-motion condition appears to be an outstanding contributor to the alteration of driver performance, Friedman's rank test indicated that no significant difference existed among the five conditions for the percentage difference measures.

Three Motion Cue Conditions

An alternate approach to the analysis of these data involved some simplification regarding the independent variable - experimental conditions. Grouping the experimental conditions according to the number of motion cues present reduced the number of levels of the treatment variable from six to three. A nominal scale of measurement described the levels of the experimental condition variable. The aforementioned grouping provided the independent variable (number of motion cues) with an interval scale of measurement. Table 8 shows a tabular description of this grouping scheme.

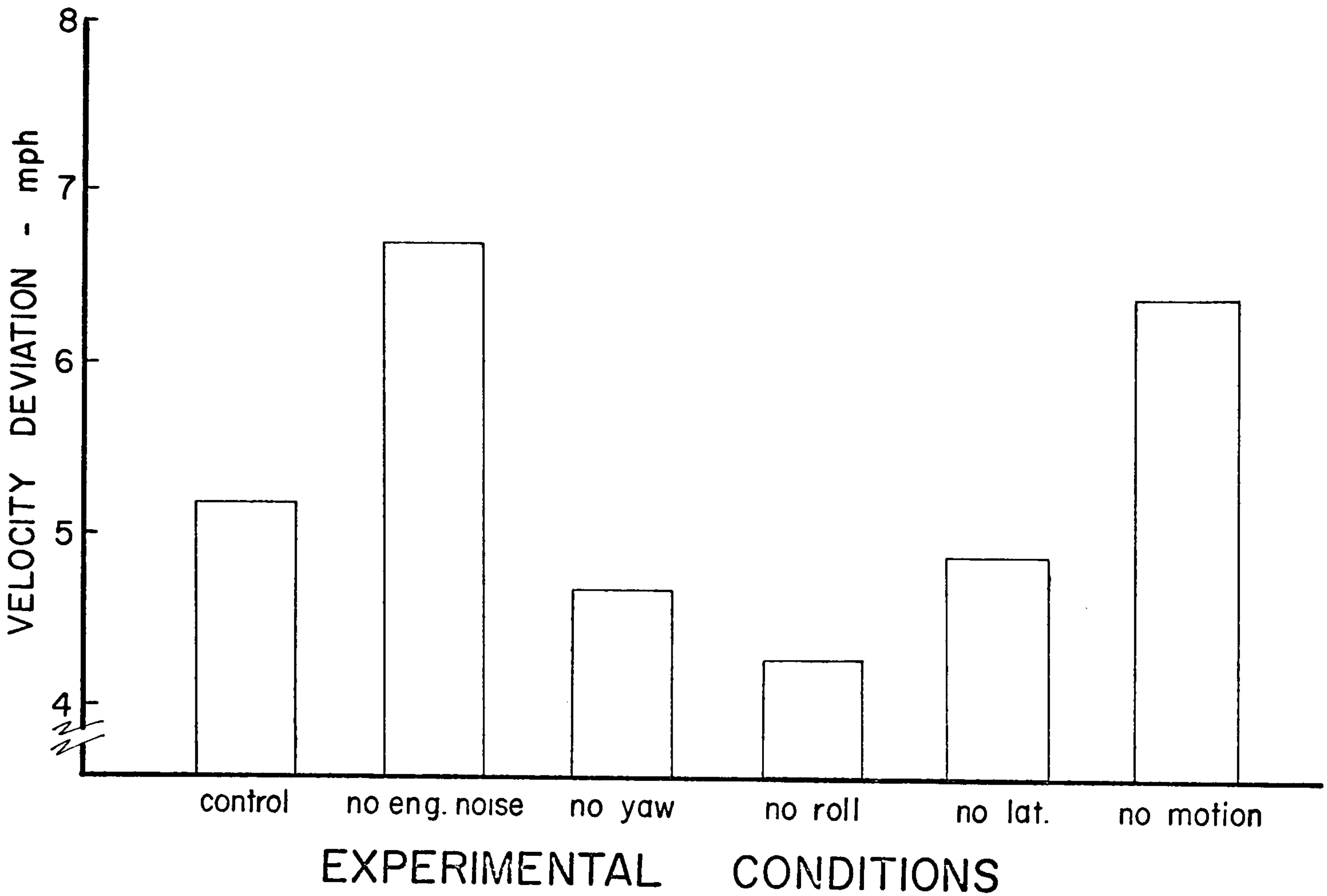

Figure 11. Histogram of velocity deviation over six experimental conditions.

TABLE 6

Analysis of Variance of Velocity Deviation over Six Experimental Conditions

Source of Variance	df	SS	MS	F
Experimental Conditions	5	1518	303.5	2.53 *
S/Exp. Conditions	42	5036	119.9	
Total	47			

* $p < .05$

TABLE 7

Percentage Differences from the Control Case of Five Performance Measures over Five Experimental Conditions

Experimental Condition	Performance Measure: Steering Reversals	Accelerator Reversals	Yaw Deviation	Lateral Deviation	Velocity Deviation	$\sum\lvert\%\rvert$
No Roll	-13.7	+20.1	+3.6	+2.7	-17.7	57.8
No Yaw	-18.9	+16.0	-2.1	+5.1	-9.6	51.7
No Lateral Trans.	-13.4	-12.2	-7.9	-8.7	-5.6	47.8
No Motion	-24.7	-4.9	+33.2	+33.7	+23.6	120.1
No Engine Noise	+3.7	+18.9	+3.8	-1.3	+27.2	54.9

TABLE 8

Grouping of Experimental Conditions by the Number of Motion Cues

Experimental Condition	No. of Motion Cues	No. of Subjects
Control and No Engine Noise	3	16
No Yaw, No Roll, No Lateral Trans.	2	24
No Motion	0	8

The results yielded by the (number of motion cues) arrangement of the treatment variable were more general than the results provided by the six experimental conditions. By hypothesis, no distinction would be possible among the contributions of roll, yaw, and lateral motion cues or the absence of engine noise to driver performance measures.

In evaluating the degree of relationship between the independent variable and the various performance measures, the six-experimental-condition approach limited the evaluation to a weak and difficult to interpret coefficient of concordance. The interval scale of measurement (of the independent variable) provided by the number-of-motion-cues grouping permitted a more meaningful Pearsonian correlation coefficient to be used in discussing the above relationship.

Analyses of the data, as grouped according to the number of motion cues, were performed in the same manner as the experimental condition analyses with the addition of a linear correlation coefficient (Pearson $\underline{r}$) relating each performance measure with the number of motion cues. Table 9 presents a summary of the statistical test results obtained in evaluating five performance measures over three motion cue conditions.

As in the previous set of analyses, the data will be dealt with on a by-performance-measure basis.

<u>Steering reversals</u>. Three groups of data (each representing conditions of a specific number of motion cues) indicating average measurements of steering reversals are shown in Figure 12. Examining the total number of reversals for each motion cue category (weighted to represent a total over eight subjects) a Chi-square test revealed that a significant difference ($\underline{p} < .001$) existed among these totals. Using the three motion cue total as the control measure, significant differences

TABLE 9

Summary of Statistical Test Results of Five Performance Measures over Three Motion Cue Conditions

PERFORMANCE MEASURE	STATISTICAL TEST: ANOVA	DUNNETT control vs :	PEARSON *r*	CHI-SQUARE: Overall	CHI-SQUARE: Control compared with : 2-Motion Case	CHI-SQUARE: Control compared with : Zero-Motion Case
Steering Reversals			.393 ($p<.01$)	109.8 ($p<.001$)	76.15 ($p<.001$)	182.9 ($p<.001$)
Accelerator Reversals			.093 (N.S.)	(N.S.)	(N.S.)	7.84 ($p<.01$)
Yaw Deviation	F=10.96 ($p<.001$)	*t*=3.83 ($p<.005$) No Motion	-.472 ($p<.001$)			
Lateral Deviation	F=7.588 ($p<.005$)	*t*=3.50 ($p<.005$) No Motion	-.459 ($p<.001$)			
Velocity Deviation	F=3.724 ($p<.05$)	(N.S.)	-.060 (N.S.)			

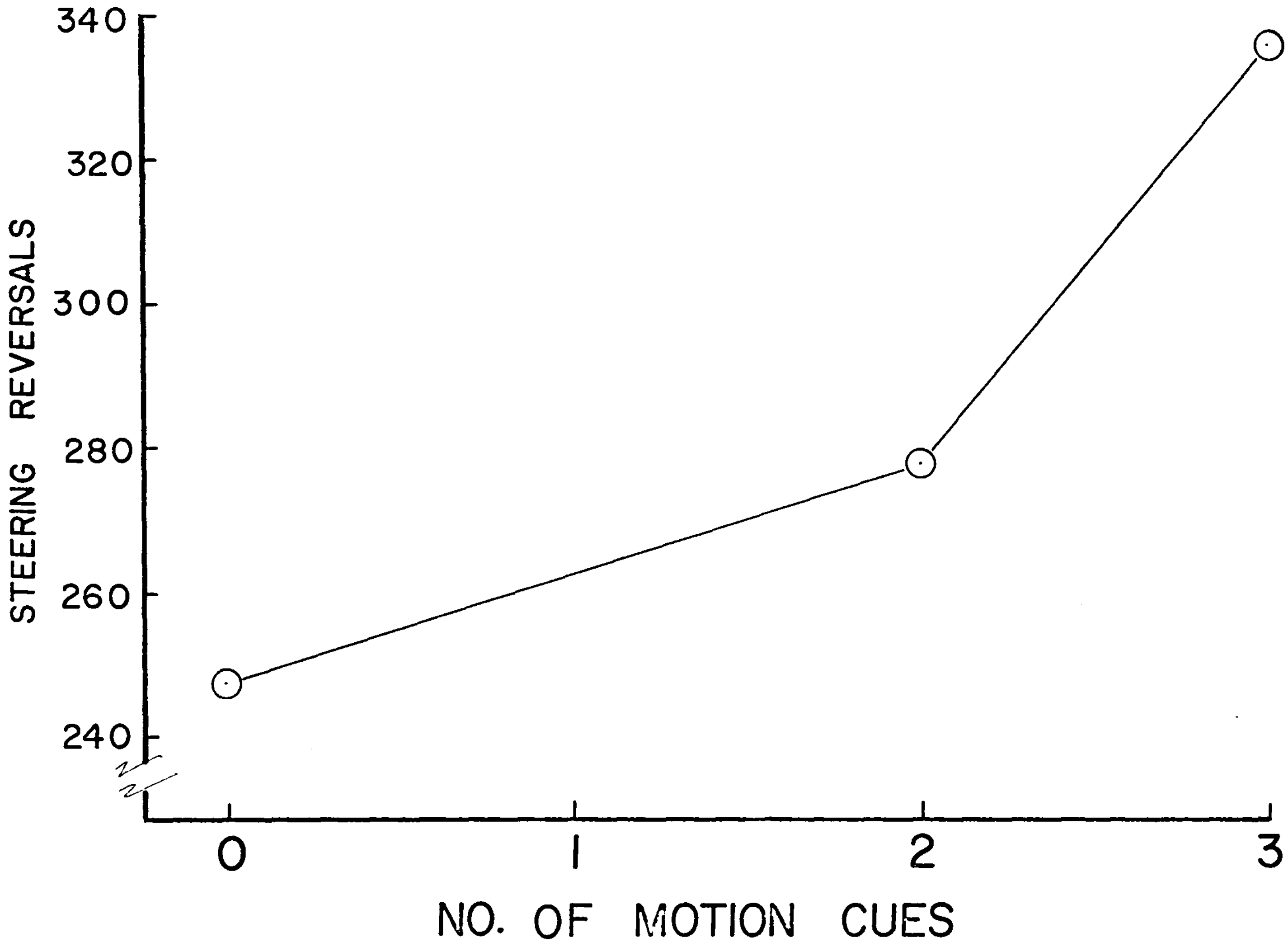

Figure 12. Steering reversals for three motion cue conditions.

were shown (by Chi-square) between the control and each of the other (zero and two) motion cue condition (Table 9).

A definite trend of an increasing number of reversals with an increasing number of motion cues is apparent. The degree of relationship between steering reversals and motion cues is reflected in the significant ($p < .01$) linear correlation coefficient of .393.

Accelerator reversals. Figure 13 shows the accelerator reversal data as a function of the three motion cue conditions. Analysis of the (weighted) totals for each motion cue condition by means of a Chi-square test showed no significant difference among group totals. However, comparison of the control (three motion case) total with that of the no motion condition revealed a significant difference according to the results of a Chi-square test (Table 9).

A non-significant correlation coefficient (.093) expressed the degree of linear relationship between the accelerator reversal measures and the number of motion cues.

Yaw deviation. The influence of the number of motion cues on measures of yaw deviation is shown in Figure 14. The significance of the F -ratio determined in the variance analysis of Table 10 ($p < .001$) indicates a significant difference among the three motion cue condition group means, while Dunnett's test specifies that only the no-motion mean is significantly different from the three-motion-case mean ($t = 3.83$, $p < .005$).

Figure 14 indicates an inverse relationship between the amount of yaw deviation and the number of motions cues. This inverse relationship is apparent in the significant ($p < .001$) negative correlation coefficient of -.472.

Lateral deviation. The lateral deviation measures presented in

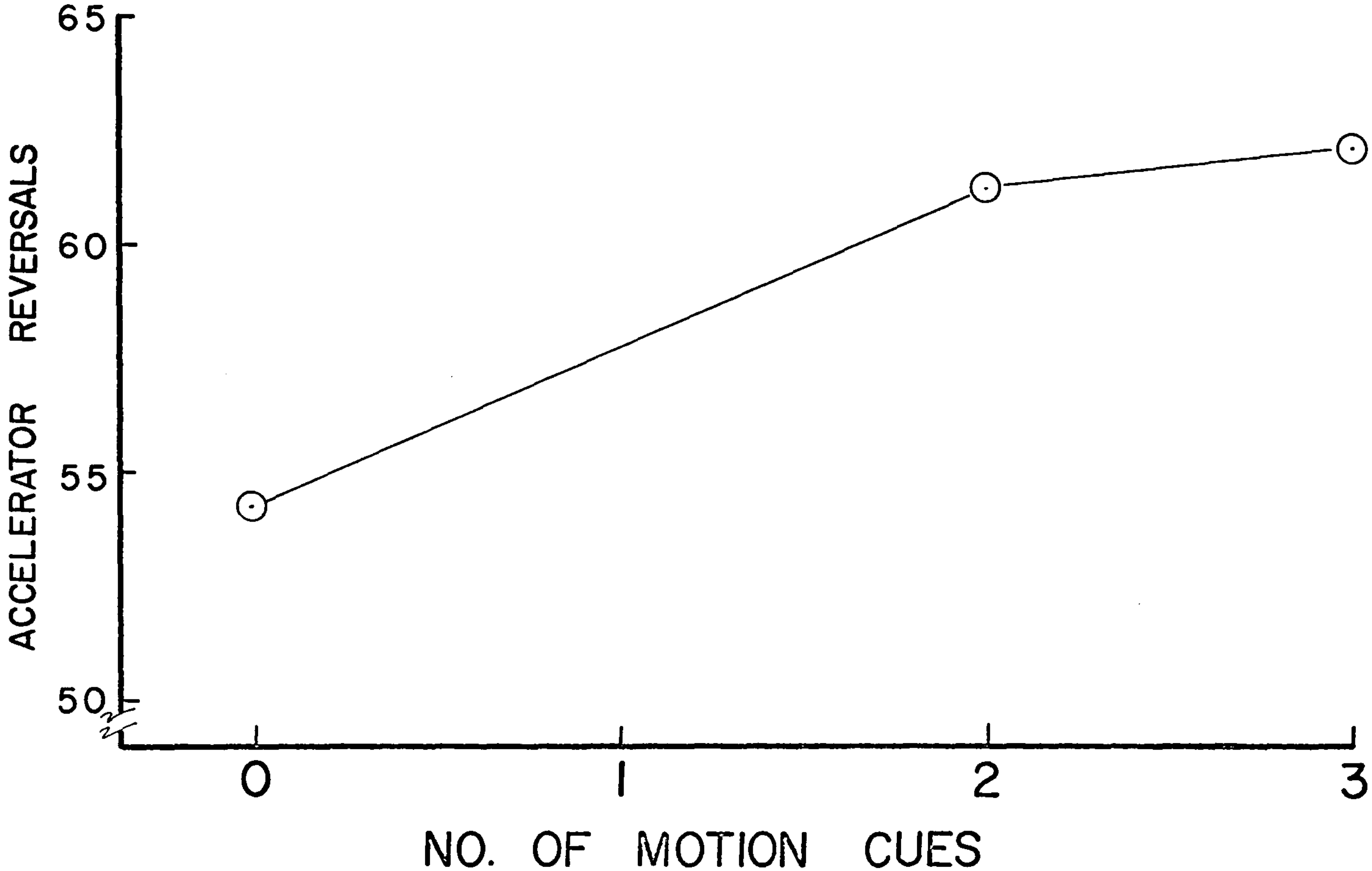

Figure 13. Accelerator reversals for three motion cue conditions.

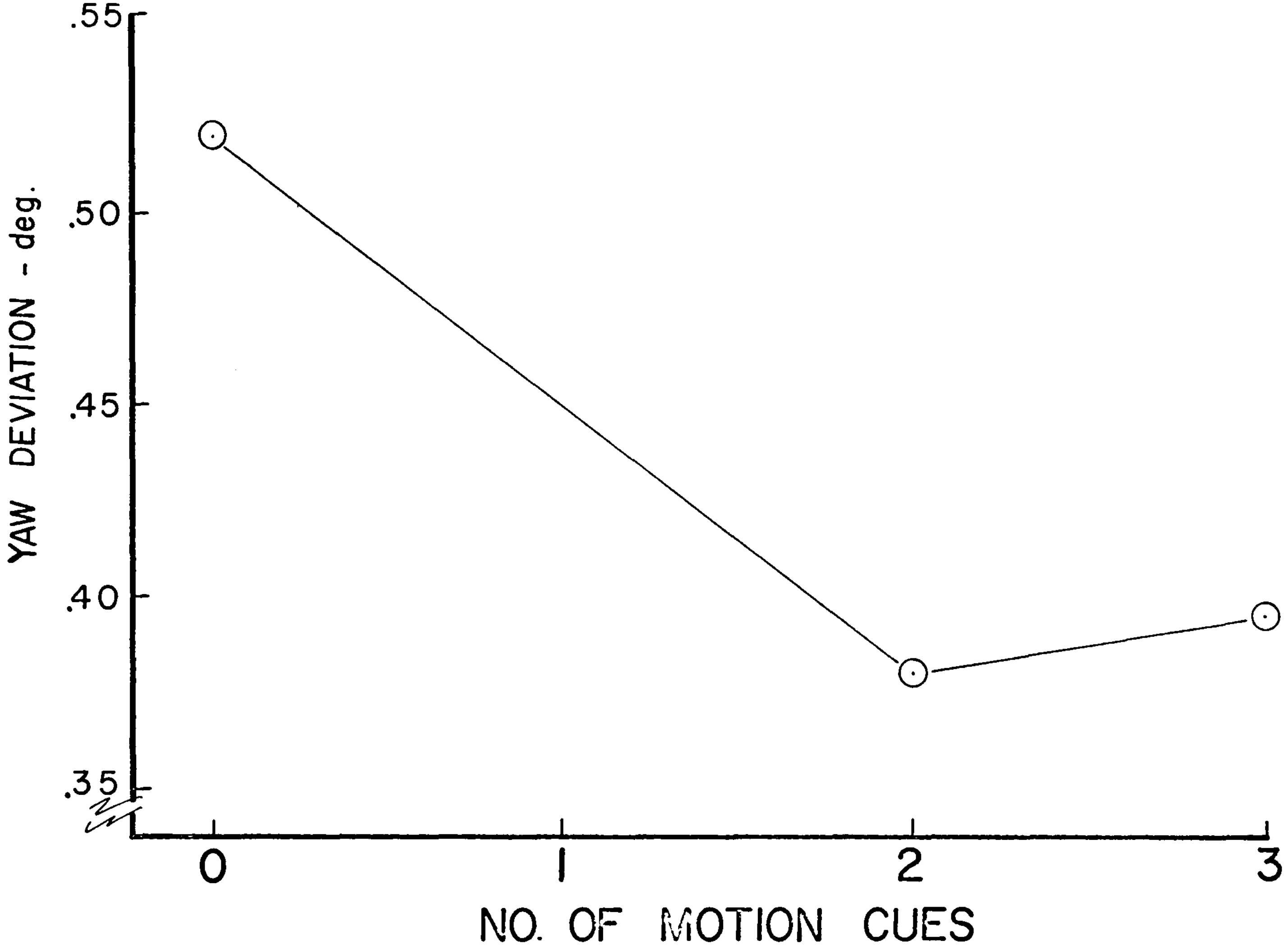

Figure 14. Yaw deviation for three motion cue conditions.

TABLE 10

Analysis of Variance of Yaw Deviation over Three Motion Cue Conditions

Source of Variance	df	SS	MS	F
Motion Cue Conditions	2	.097	.049	10.96*
S/Motion Cue Cond.	45	.201	.0045	
Total	47			

* $p < .001$

Figure 15 show the same type relationship to the number of motion cues as did the yaw deviation measures of Figure 14. The mean lateral deviation measures for the two and three motion cue cases are identical.

Variance analysis (Table 11) indicates that the number of motion cues is a significant ($p < .005$) factor in the variation of lateral deviation measures. The no-motion case exhibited a significantly higher lateral deviation measure than the three-motion case according to Dunnett's test ($t = 3.50$, $p < .005$).

As in the yaw deviation measures, the significant ($p < .001$) negative correlation coefficient (-.459) gave support to the apparent negative trend shown in Figure 15.

Velocity deviation. Three groups of velocity deviation measures are plotted against the number of motion cues in Figure 16. Variance analysis (Table 12) indicates a significance level of $p < .05$ in evaluating the differences among the three motion-cue group means.

Dunnett's test revealed that neither of the remaining group means (zero and two-motion cues) was significantly different from that of the three-motion cue control group.

The degree of relationship shown by the linear correlation coefficient (-.060) was not significantly different from zero, as expected from the results of the Dunnett's tests.

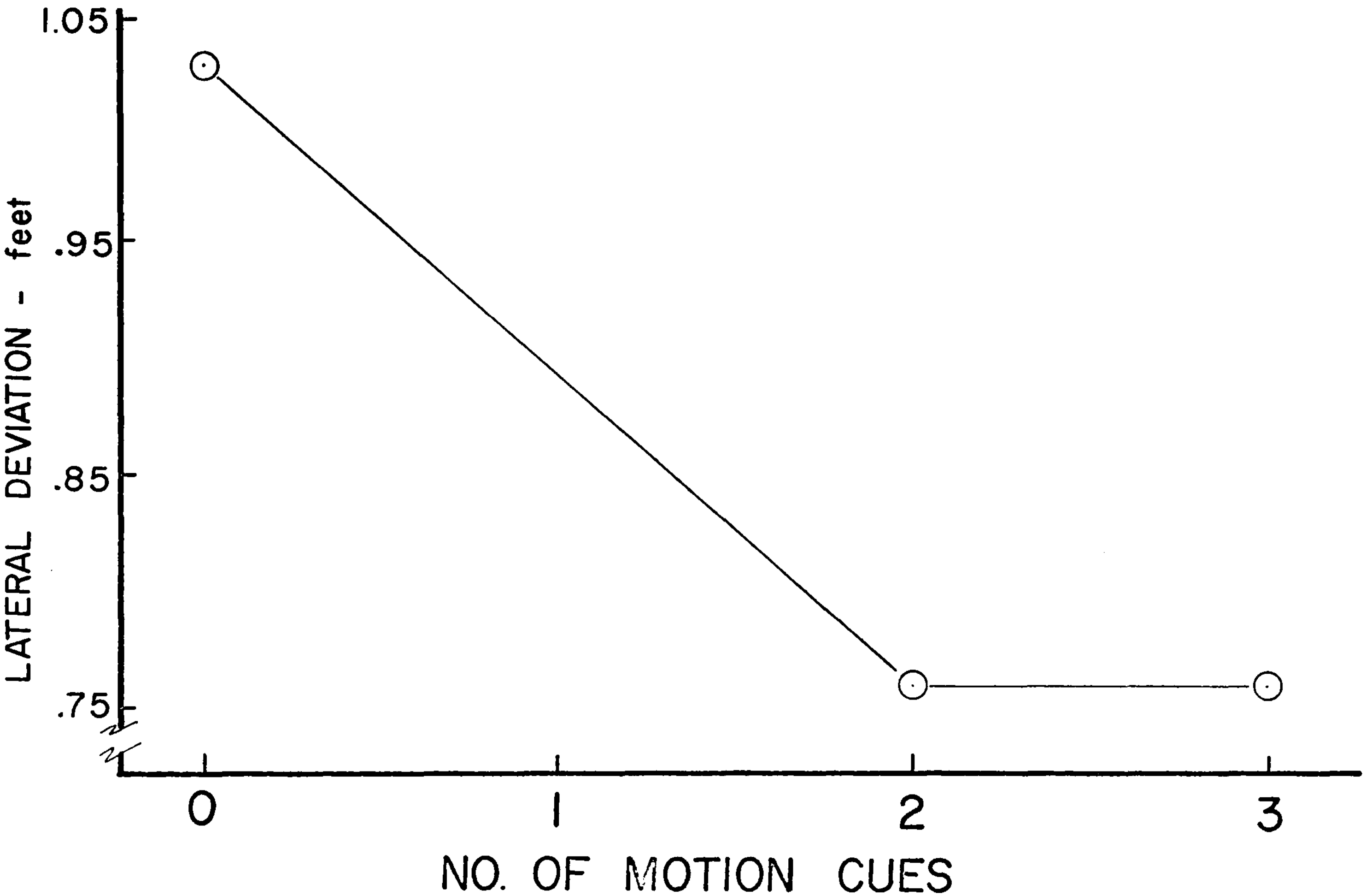

Figure 15. Lateral deviation for three motion cue conditions.

TABLE 11

Analysis of Variance of Lateral Deviation over Three Motion Cue Conditions

Source of Variance	df	SS	MS	F
Motion Cue Conditions	2	.129	.065	7.588
S/Motion Cue Cond.	45	.382	.0085	
Total	47			

* $p < .005$

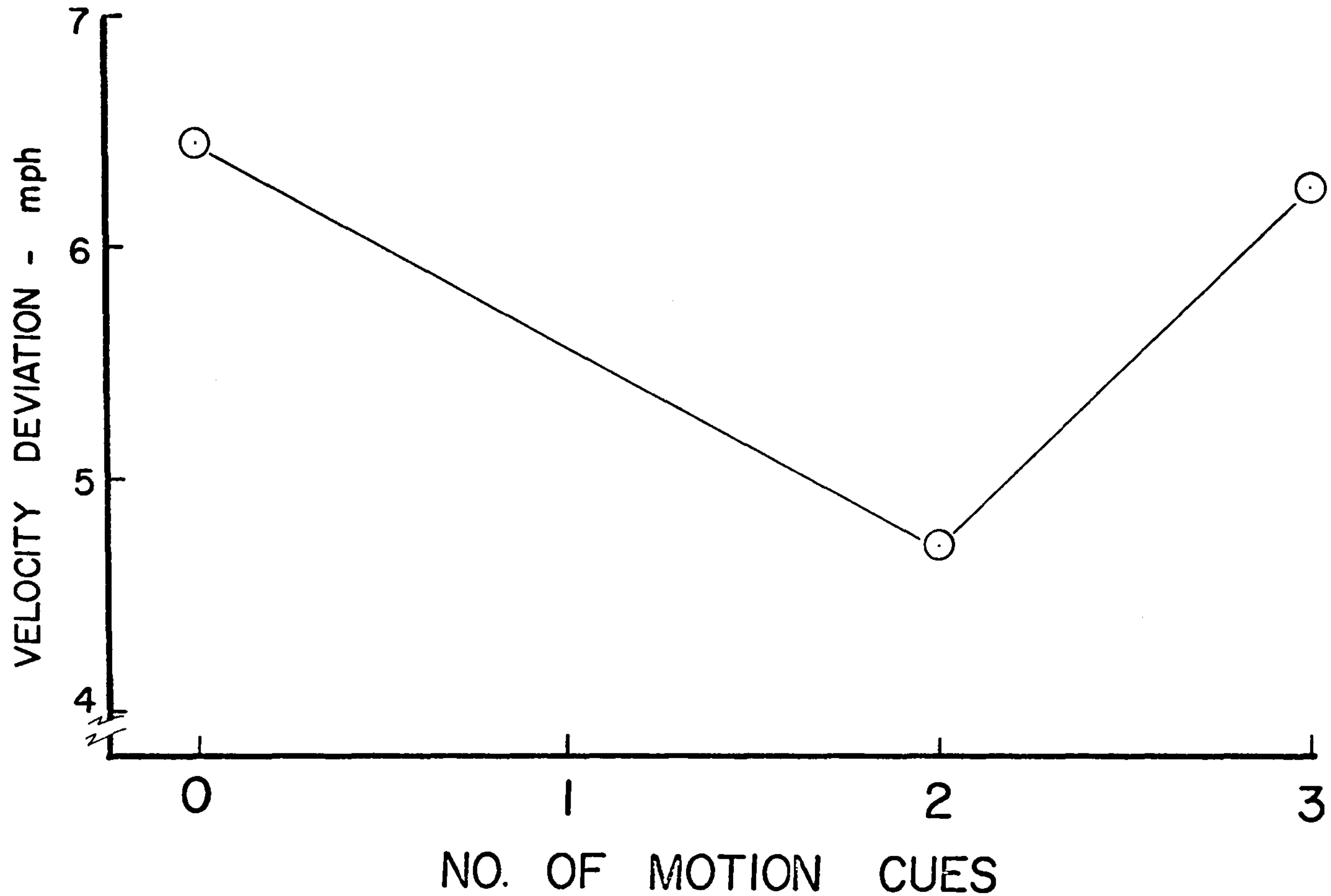

Figure 16. Velocity deviation for three motion cue conditions.

TABLE 12

Analysis of Variance of Velocity Deviation over Three Motion Cue Conditions

Source of Variance	df	SS	MS	F
Motion Cue Conditions	2	932	466	3.724*
S/Motion Cue Cond.	45	5631	125.1	
Total	47			

* $p < .05$

DISCUSSION AND RECOMMENDATIONS

The general and most obvious conclusion to be drawn from the results of this research is that driver performance in a simulator is significantly influenced by the combination of motion and audio cues that is presented.

Two types of driver performance measures were used in this study: operator input measures (steering and accelerator reversals); and system output or tracking error measures (yaw, lateral, and velocity deviation). In view of the reservations of this author and the skepticisms of others (McLean and Hoffman, 1973) concerning the use of steering and accelerator reversals as a measure of driver performance, the results reflected in the three deviation measures (above) will be emphasized.

Motion Cue Influence

It was clearly shown (Table 3) that the ability to control vehicle direction, position, and speed (as measured by yaw, lateral, and velocity deviation, respectively) was significantly affect by the six combinations of motion and audio cues in this study. In particular, the deletion of all three motion cues (the no-motion condition) revealed significant differences (compared with the control case) with respect to the yaw and lateral deviation measures. Also, it should be noted from Figures 13 and 14 that the yaw and lateral deviation measures for the two-and-three-motion cue cases are very similar. It can be shown that, for these measures, the deletion of one motion cue produces results almost indentical to the control case, suggesting that two motion cues provide almost the same fidelity as three. Although not significant, using Dunnett's test, it is interesting to note from Figure 11 that the deletion of all motion had almost the same effect on the velocity deviation measure as did the absence of the audio (engine noise) cue.

Assuming driver performance to be reliably measured by, and to vary inversely as, the tracking error measures of yaw and lateral deviation, the negative correlation coefficients of -.472 and -.459, respectively (Table 9) lend strong support to the hypothesis that driver performance is augmented by the addition of motion cues. This relationship of improved performance with an increased number of motion cues can also be supported by the velocity deviation data. However, the grouping scheme of Table 8 combines the group with the highest velocity deviation measure (no engine noise) with the group having the lowest measure (control). This nullifies the otherwise apparent trend of an improved ability to maintain an instructed speed as a function of an increased number of motion cues.

With respect to the individual cues of roll, yaw and lateral translation, the effects of deleting one cue, e.g. roll, were almost indistinguishable from the effects of deleting either of the other two. The only noteworthy exception to this similarity of effect was the accelerator reversal measure under the no-lateral-translation condition (Figure 8). The composite summary across all five performance measures (Table 7) displays the similarities reflected by the deletion of each cue.

When evaluated as a function of the number of motion cues (Table 12), the steering reversal measure is significantly influenced by the variation in motion cues. In light of the previously substantiated hypothesis of augmented driver performance as a result of an increased number of motion cues, the significant positive correlation between steering reversals and number of motion cues is worthy of some discussion. In its traditional, yet somewhat suspect, applications as a performance measure the number of steering reversals is generally thought to vary inversely with driver performance. The apparently opposite trend shown in this study can be attributed to increased kinesthetic feedback provided by an increased number of motion cues. It is suggested that the increased feedback enables the driver to detect otherwise sub-threshold tracking errors and consequently permits him increased opportunities for correcting these errors with steering maneuvers.

Audio Cue Influence

Although no statistically significant effects of the deletion of the audio cue were determined, Table 7 shows that this deletion had the greatest influence on the velocity deviation measure. It is interesting to note that although the absence of motion contributed substantially (23.6% more than the control group) to a degraded performance in maintaining the instructed speed (70 M.P.H.), the absence of the audio cue had virtually no effect on the ability to maintain direction and position of the simulated vehicle.

In corroboration of the aircraft-oriented findings of Young (1967) and Bergeron (1970), the results of this research clearly support the thesis that moving-base simulation is superior to fixed-base simulation with respect to operator performance. Performance measures of yaw deviation and lateral deviation demonstrated significant decreases with the collective addition of roll, yaw, and lateral translation cues to an otherwise fixed-base simulator.

Although statistical significance was not shown, the deletion of a velocity dependent audio cue also appeared to contribute to the inability of the driver to maintain an instructed vehicle speed.

The results of this study suggest the following driving simulator design criteria for adequate simulator fidelity:

1) the incorporation of at least two of the three motions of roll, yaw, and lateral translation, and

2) the presentation of a velocity-dependent audio cue.

Based on statistically insignificant results and some conjecture it is suggested that simulator fidelity might vary according to the combination of motion and audio cues presented. The following scale (Table 13) might serve as a guide for relative fidelity comparisons.

TABLE 13

Relative Simulator Fidelity Scale based on Combinations of Motion and Audio Cues

Increasing Simulator Fidelity ↑

Number of Motion Cues (Roll, Yaw, Lateral Trans.) Presented	Presentation of (Velocity-related) Audio Cue
3	Yes
3	No
2	Yes
2	No
1	Yes
1	No
0	Yes
0	No

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APPENDIX A

Instructions to Subjects

The purpose of this experiment is to determine how simulator visual, auditory and motion cues affect driver performance. As a subject you will be seated in the driver's position of an automotive mock-up. You will be presented with a visual display consisting of a moving, geometrical roadway simulation and a dashboard speedometer. During operation of the simulator you will experience simulated vehicle motions corresponding to the driving conditions and your control maneuvers. Your control of the simulator's speed and road position will be by means of a standard steering wheel and accelerator pedal in a normal automotive configuration. After being seated on the platform you will be given instructions by, and may communicate with the experimenter via the dash mounted (upper right) speaker/microphone.

Driving conditions will vary in the course of the experiment (including the preliminary practice drive). Visual and motion disturbances corresponding to headwinds and lateral gusts as well as roadway curvature will be introduced separately and in combination.

It should be emphasized that this experiment is concerned with driver performance in normal highway driving. As you perform the instructed tasks, please keep in mind that normal highway driving behavior is expected from you.

During the experiment you will be asked to perform three types of tasks:

1. Maintain nominal right or left lane position.
2. Make instructed speed changes (between 30 and 90 mph).
3. Execute normal and sudden lane changing maneuvers.

It might be helpful to keep these tasks in mind during your preliminary practice run.

The experimental procedure will be as follows:

1. Be seated in driver's seat; adjust seat position and fasten safety belt.

2. Become familiar with controls, speaker/microphone, and emergency motion cut-off button.

Note: Activation (1 push) of the emergency motion cut-off button halts all motion of the simulator platform. If at any time during the experiment you sincerely feel that continued simulator operation would not be agreeable with you, please verbally notify the experimenter and depress (once), the emergency motion cut-off button. You may leave the platform (to the left only) if and only if all platform motion has stopped.

3. Communications checkout and questions.

4. Take a 5 min. preliminary practice drive.

5. Upon instruction from experimenter,leave simulator and take 5-minute break.

6. Return to simulator and fasten seat belt.

7. Communications check out and questions.

8. Experimental data collection run (9 min.) during which instructions will be given by the experimenter.

9. Upon instruction,leave simulator and complete the experiment evaluation form.

TABLE B-1

Data Summary of Five Performance Measures for Eight Control-group Subjects

	Performance Measure				
Subject No.	Steering Reversals	Accelerator Reversals	Yaw Deviation	Lateral Deviation	Velocity Deviation
18	532	86	.39	.34	5.39
19	254	46	.33	.56	5.43
20	230	28	.40	.42	4.59
21	290	52	.42	.49	6.04
22	271	56	.33	.40	3.80
23	301	81	.34	.39	6.58
24	394	52	.32	.36	4.80
25	349	52	.25	.26	4.23
Mean	328	56.7	.35	.40	5.21
Stnd. Dev.	97.8	18.6	.05	.09	.93

TABLE B-2

Data Summary of Five Performance Measures for Eight No-Motion-group Subjects

Subject No.	Performance Measure				
	Steering Reversals	Accelerator Reversals	Yaw Deviation	Lateral Deviation	Velocity Deviation
10	210	35	.68	.79	4.90
11	233	79	.55	.69	5.83
12	218	48	.44	.40	10.36
13	324	25	.33	.46	5.72
14	237	49	.50	.51	5.89
15	243	68	.39	.59	4.87
16	272	53	.43	.44	5.86
17	235	75	.36	.44	6.37
Mean	247	53.9	.46	.54	6.44
Stnd. Dev.	36.3	19.0	.11	.14	.75

TABLE B-3

Data Summary of Five Performance Measures for Eight No-Roll-group Subjects

Subject No.	Performance Measure				
	Steering Reversals	Accelerator Reversals	Yaw Deviation	Lateral Deviation	Velocity Deviation
26	202	69	.33	.42	3.70
27	346	68	.38	.33	3.82
28	313	105	.41	.49	3.55
29	283	58	.33	.36	4.40
30	329	67	.41	.46	4.96
31	187	63	.35	.41	4.77
32	301	37	.33	.47	5.03
33	306	77	.32	.38	3.80
Mean	283	68.1	.36	.42	4.29
Stnd. Dev.	58.1	19.0	.04	.06	.61

TABLE B-4

Data Summary of Five Performance Measures for Eight No-Yaw-group Subjects

Subject No.	Performance Measure				
	Steering Reversals	Accelerator Reversals	Yaw Deviation	Lateral Deviation	Velocity Deviation
1	152	25	.27	.40	4.02
3	174	24	.46	.62	5.61
4	363	23	.44	.36	4.50
5	256	52	.34	.44	4.46
6	230	60	.31	.38	5.12
7	263	66	.30	.39	4.25
8	307	79	.27	.33	5.90
9	379	198	.32	.47	3.23
Mean	266	65.8	.34	.42	4.64
Stnd. Dev.	81.7	57.4	.07	.09	.87

TABLE B-5

Data Summary of Five Performance Measures for Eight No-Lateral Trans.-group Subjects

Subject No.	Performance Measure				
	Steering Reversals	Accelerator Reversals	Yaw Deviation	Lateral Deviation	Velocity Deviation
34	329	43	.25	.29	4.36
35	296	48	.33	.33	4.14
36	345	29	.33	.50	6.79
37	167	58	.34	.43	3.91
38	299	62	.34	.41	5.44
39	286	50	.32	.37	4.90
40	301	51	.28	.27	4.59
41	246	58	.29	.31	4.52
Mean	284	49.8	.31	.36	4.90
Stnd. Dev.	55.5	10.4	.03	.08	.92

TABLE B-6

Data Summary of Five Performance Measures for Eight No-Engine Noise-group Subjects

Subject No.	Performance Measure				
	Steering Reversals	Accelerator Reversals	Yaw Deviation	Lateral Deviation	Velocity Deviation
42	290	88	.35	.39	4.98
43	289	35	.40	.45	4.77
44	286	35	.31	.44	7.36
45	390	70	.27	.34	7.06
46	470	79	.29	.29	8.02
47	434	81	.42	.39	13.19
48	302	30	.42	.51	3.70
49	260	122	.34	.36	4.72
Mean	340	67.4	.35	.40	6.73
Stnd. Dev.	79.4	32.1	.06	.07	3.03

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THE INFLUENCE OF MOTION AND AUDIO CUES ON DRIVER PERFORMANCE IN AN AUTOMOBILE SIMULATOR

by

Robert C. McLane

(ABSTRACT)

A highway driving simulator with a computer-generated visual display, physical motion cues of roll, yaw, and lateral translation, and velocity dependent sound/vibration cues was used to investigate the influence of these cues on driver performance.

Forty-eight student subjects were randomly allocated to six experimental groups. Each group of eight subjects experienced a unique combination of the motion and audio cues. The control group performed under a full simulation condition while each of the remaining five groups performed with certain combinations of motion and sound deleted. Each driver generated nine minutes of continuous data from which five performance measures were derived. Results indicate that the performance measures of yaw, lateral and velocity deviation are significantly affected by the deletion of cues. In support of the hypothesis that driver performance is augmented by the addition of motion cues, significant negative correlations were shown between the number of motion cues present and the measures of yaw and lateral deviation. With respect to motion and audio cues, recommendations were made regarding simulator design criteria and relative simulator fidelity comparisons.