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Sharing Control Between Human and Automation Using Haptic Interface: Primary and Secondary Task Performance Benefits

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***Abstract*— In this paper, a paradigm for human/automation control sharing is described in which a machine's manual control interface is motorized to allow a human and an automatic controller to exert control simultaneously. The manual interface becomes a haptic display, relaying information to the human about the actions of the automatic controller. While perceiving the automation actions, the human may express his control intentions in a way that either overrides the automation or conforms to it. Because the human remains tightly integrated in the primary control task, he retains responsibility and awareness even while giving away a portion of the workload to the automation. The objective of this paper is to demonstrate how adding automation by motorizing the manual interface can be used not only to improve performance on a primary task, but also to reduce perceptual demands or free attention for a secondary task. Results are presented from 3 experiments in which 11 subjects completed a path following task using a motorized steering wheel on a fixed-base driving simulator. The automation system behaved like a co-pilot who had a hand on the steering wheel, could see the road (but not certain obstacles,) and would assist with path following by applying torques to the steering wheel through a relatively light spring. Results indicate that haptic assist applied through the steering wheel improves path following by least 30%, $p<$0.0001 while either reducing visual demand by 29%, $p<$0.0001, or improving reaction time in a secondary tone localization task by 18 ms, $p=$0.0009. Whereas the presence of a secondary task adversely affected lane keeping performance without haptic assist, there was no dependence of path following performance or obstacle avoidance on the presence of a secondary task when haptic assist was provided. Potential applications of this research include the design of interfaces based on haptic display that support sharing of control between a human operator and automation system.**

I. INTRODUCTION

While certain costs of adding automation to a machine or process were easy enough to anticipate (additional operator training, for example), other costs have turned out to be much more subtle. Especially when operators are called upon to share control with an automation system, unexpected problems arise. These include bumpy transitions between automated and manual control [Mosier, 2002], [Meyer et al., 2001] and *automation surprises* that occur when the operator has a poor mental image of automation behavior or misses automation mode changes [Sarter et al., 1997]. The consequences arising from these unexpected problems can be dire, at times offsetting the improved precision and performance or reduced operator workload for which automation was added in the first place. Unravelling these costs and providing solutions has been the focus of much research in recent years.

A portion of the unexpected problems associated with sharing control between a human operator and automation system can be attributed to the need for the operator to master two control interfaces and to learn two or more distinct operating modes. Whereas many machines present a manual control interface requiring continuous, direct control and certain manual skills, the typical automation interface presents a set of indicators, knobs, and buttons requiring intermittent input and certain analytical and decision making skills [Mosier, 2002]. When complex or unanticipated conditions arise, the traditional approach to 'cooperation' is for the operator to interrupt the automation and take over full control through the manual interface [Christoffersen and Woods, 2002]. Upon wresting control away from the automation system, the advantages of automation (precision, computational speed, and other functions) are lost [Christoffersen and Woods, 2002]. Bainbridge [Bainbridge, 1983] has noted that ironically, the manual skills of an operator who regularly gives up control to an automation system may begin to degrade from lack of practice, leaving him ill-prepared to meet the heightened challenges that typically arise during automation failures. What is needed is an intermediate, more collaborative mode of interaction. Ideally, the operator would be able to negotiate with and re-direct the automation system without first disabling it and then re-starting [Christoffersen and Woods, 2002]. There would be a natural kind of "give and take" between the operator and the automation. In this paper, we propose an automation interface and associated control sharing paradigm that does not include mode switching and therefore avoids the associated pitfalls. The operator need learn only one interface and one set of rules.

Another portion of the unexpected problems in automation can be attributed to the poor rate and quality of information transmission supported by most automation interfaces. In addition to the communication of current mode and action, efficient cooperation requires the communication of goal and intent. One approach to improving communication is the use of multimodal displays. Sarter has estimated the value of various modalities for guiding the attention of the operator and effectively managing interruptions [Sarter, 2002]. To visual and auditory displays, Sarter adds haptic (kinesthetic and tactile) display, including vibrotactile cues on the manual control interface.

In automobile interface, both vibrotactile and pulse torque cues applied through a motorized steering wheel have been tested as a means of informing or warning automobile drivers [Schumann et al., 1992], [Suzuki and Jansson, 2003], [Driver and Spence, 2004]. In addition to discrete cues, haptic display has been used to automate vehicle steering in such a way that the drive can continuously monitor the automation actions [Switkes et al., 2004]. In this work, automation took the form of a virtual potential field to aid the driver in lane-keeping. Any deviation from the center of a lane produced continuous haptic information about the automation's tendency to return the vehicle to the lane center.

In this paper, we also employ haptic display with the aim of enabling more effective negotiation and coordination of intent and actions. The promise of haptic display follows in part from its lack of overlap with the visual and auditory modalities. But further, haptic signals can be information rich in ways that are particular to the communication of intent, especially intent involving direction and magnitude. Further, we believe that signals encoded in force and motion are especially suited for informing the operator about automation intent because they can simultaneously convey intent *and* automation confidence in that intent. Mechanically mediated communication can even support negotiation of authority. For example, a particular motion imposed by the automation can be accompanied by larger reaction forces that resist motion inputs from the operator. Likewise, the operator could express his desire for increased authority by using high impedance or less 'give', possibly by co-contracting the muscles in his arm. This is the way two human operators would communicate if they both grasped the same manual control interface: each operator would apply muscle action to extract their own desired response with a certain authority while simultaneously perceiving the other's intent and desire for authority by feel.

We propose, then, to combine the machine and automation interfaces into a single interface modeled after the traditional manual control interface. The human operator is presented only the standard manual interface over which the automatic control system is also given authority. The automation system imposes its control effort through a motor coupled directly to the interface. The motorized manual interface becomes a haptic display, relaying information about the actions of the automation system to the human operator's haptic senses. In effect, we propose a return to the "contact" or "direct" mode of interaction, where visual/kinesthetic perception and motor response are relied upon rather than the analytical and decision making skills usually required by the automation system. In contrast to the use of vibrotactile cues for alert and display of discrete information, we use haptics to relay continuous signals to the operator. In our shared control scheme, the automation is placed in mechanical parallel with the operator and takes the form of an assist that actually intervenes in the control loop. The operator may choose either to yield to the assist while observing its action, or override it by exerting slightly more effort.

Through the motor on the interface, the automation may apply torques according to its own rules or control law, as a function of sensed machine state. For example, a steering wheel can be given a 'home' position that is itself animated according to sensed vehicle position within a lane. The automatic controller can create virtual springs that attach the steering wheel to a moving home angular position that corresponds to the vehicle direction recommended by the automation. By feel, the operator can form a mental image of the springs attached to the moving home position, especially by haptically exploring the invariants of the reaction torque to his own input motions. To ensure that it can be overridden, the automation uses a limited mechanical impedance (essentially a limited stiffness).

The introduction of assist through a motor on a manual control interface has been studied extensively in the applications of haptic interface to teleoperated and virtual environments [Hayward et al., 2004] [Gillespie, 2004]. In these applications, assist is offered in the form of *virtual fixtures* that may be used by the operator as mechanical guides for controlling force or motion direction. Virtual fixtures have been shown to improve performance in targeting tasks [Hasser et al., 1998] [Dennerlein and Yang, 2001], peg-in-hole tasks [Rosenberg, 1993] [Sayers and Paul, 1994] [Payandeh and Stanisic, 2002] and in surgical interventions [Park et al., 2001]. Virtual fixtures are usually fixed in the shared workspace; however, virtual fixtures whose composition were functions of time or recognized operator motions were studied in [Li and Okamura, 2003]. In this work we also employ virtual fixtures, created by the automation in the workspace shared by the automation and operator. Our fixtures, however, are animated by the automation system. By and large, the focus in the field of haptic interface has been improved human/machine performance. The possible secondary benefits, such as reduced operator workload, have been overlooked in this literature.

The setting for our investigation of mechanically mediated control sharing is a driving simulator with a motorized steering wheel. While our particular implementation is far removed from actual driving—our former setups were in fact closer [Steele and Gillespie, 2001],—we hope that our results may nevertheless contribute to ongoing work in the design of automation interfaces for driving. The primary goal in this paper is to quantify the primary and secondary benefits of using a motorized interface to institute control sharing between an operator and an automatic controller.

We present three experiments designed to demonstrate our conception of shared control using a motorized manual control interface. Naturally, an expected outcome is improved performance on the semi-automated task, which is quantified in the first experiment as described in section III. However, there are other expected benefits. The second experiment, described in section IV, is aimed at quantifying the benefits in reduced visual demand associated with the primary task. In the third experiment, described in section V, we investigate the hypothesized freeing of attention (as reflected by improved performance on a secondary task). The driving task in all experiments also includes a challenge not addressed by the automatic controller, which becomes a means for prompting negotiations between the human and automation, and a basis for requiring and measuring maintained attention to the primary driving task. Section VI compares results from all three experiments and discusses the effects of haptic assist on primary and secondary tasks, and section VII summarizes our results.

II. METHODS

To carry out our experiments, we developed a fixed-base driving simulator that featured a computer monitor and a motorized steering wheel. The computer monitor presented participants with a view of the simulated vehicle hood and roadway, and the motorized steering wheel provided steering control and force-feedback from the simulated tire/road interactions. In addition, the motor on the steering wheel was used to apply torques from the automation system when it was enabled. These torques were designed to assist the driver in holding the center of the simulated roadway, that is, to assist in lane-keeping. Since the automation-produced torques can be felt by the participant's hand on the steering wheel, we refer to them as haptic assist. To prompt the participants to maintain some amount of authority while being assisted by the automation, obstacles were placed in the center of the roadway. The automation system was not able to sense and avoid these obstacles. The participants were instructed that they would be solely responsible for steering around the obstacles. In this section we introduce each of the major components of the driving simulator in turn: the vehicle, roadway, and obstacle models, the automation system (including its path-planning algorithm and feedback control law), and the simulator hardware. The experimental procedures pertaining to each of the three experiments and the associated performance metrics will be described in the sections to follow.

A. Vehicle, Roadway & Obstacle Models

Participants drove a vehicle model that rolled on flat ground and turned right or left by steering the front wheels as in a typical car. The speed of the vehicle's front wheel was fixed at 15 mph, thus interactions with brake and accelerator pedals were not included. The kinematics of the vehicle model were computed according to the bicycle model, assuming no slip between the tires and the roadway [Gillespie, 1992]. Force feedback on the motorized steering wheel reflected the vehicle model's self-aligning torque. This torque acts on the steering linkage and tends to turn the front wheels into the direction of travel of the vehicle, causing the vehicle to steer straight. Given the fixed speed of the vehicle, the self-aligning torque was proportional to the steering angle of the front wheels relative to the vehicle centerline.

A roadway was defined as a sequence of 16 straight and 15 left and right curved road segments of varying length totalling 1993 meters. An overhead view of the roadway is shown in Fig. 1. All the curved segments had a curvature of $0.025\ \mathrm{m}^{-1}$. To smooth transitions, segments were joined with clothoid curves 5.6 meters long. Given the fixed front wheel speed, each trial lasted nearly 5 minutes, where some variation in the time per trial arose due to the difference in length of the actual vehicle path compared to the length of the road centerline. Visually, the road segments had a gray, concrete texture with a yellow stripe along the center and green embankments to either side.

Participants were instructed to follow the yellow centerline of the road, except when they encountered orange cylindrical objects that had been placed on the road centerline at irregular intervals. All obstacles were 1.4 meters in diameter and 2.0 meters tall, and the spacing between obstacles varied from 20 to 80 meters in a uniform random distribution. Obstacles were located on both straight and curved segments, as indicated in Fig. 1. If the vehicle perimeter contacted an obstacle, a brief orange flash indicated the collision and destruction of the obstacle.

B. Automation System

In half the trials, an automation system assisted participants in lane-keeping. Conceptually, the automation divided the steering task into two problems:

generating a desired path that would return a stray vehicle to the road centerline and turning the steering wheel to follow that desired path.

The path-planning employs a geometric approach based on knowledge of the vehicle's position and orientation relative to the nearby road geometry. This approach follows the predictive driver model of Hess and Modjtahedzadeh [Hess and Modjtahedzadeh, 1990], using the notion of an "aim-point" ahead of the vehicle on the centerline of the road. This aim-point is located by finding the closest point to the vehicle on the road and then moving that point forward 10 meters along the road. The geometry of the aim-point construction is illustrated in Fig. 2. If the vehicle's front wheels are always headed toward the aim-point, they follow a path that leads back to the center of the road. Given the desired front wheel heading and the current vehicle heading, the desired steering wheel angle is determined. Because our path-planning was based on a model of human driver behavior, we surmised that the automation would, in some sense, not fight the human driver but rather mimic the driver's behavior. This path-planning technique was also advantageous because the desired steering angle was relatively simple to calculate from the geometry; the only challenge was calculating the closest-point in real-time. We addressed that problem by using a feedback-stabilized closest-point algorithm which features computational efficiency for real-time applications [Patoglu and Gillespie, 2004].

After calculating the desired steering angle, the remaining task of the automation was to exert an appropriate torque on the steering wheel. A virtual torsional spring was used to oppose motion of the steering wheel away from the desired steering angle. That is, a restoring torque proportional to the difference between the desired steering wheel angle and the current measured angle was applied to the motorized steering wheel. A torsional stiffness of 1.2 Nm/rad set the level of control authority exerted by the automation. As a further limit on the automation's authority, the maximum magnitude of the torque was set to 0.82 Nm. Thus if the participant turned the wheel far away from the desired steering angle, the resistance imposed by the steering wheel motor would saturate well below the limits of human strength.

C. *Simulator Hardware*

Participants drove the simulator while seated in front of a computer monitor that displayed the roadway, with their right hand grasping the motorized steering wheel as depicted in Fig. 3. The motorized wheel is described in [Gillespie et al., 2003]. The computational hardware supporting the driving simulator included two computers: a PC for graphical display and data logging, and a Motorola MPC555 microcontroller for real-time simulation of the vehicle model and the automation system. An OpenGL graphics application running on the PC rendered a 3-D animation of the hood of the car and the road. A screen-shot from the animation is shown in Fig. 4, showing embankments on either side of the road and two obstacles on the centerline. The graphics software received the vehicle state information every 8 ms through a serial communication link to the MPC555 microcontroller. For Experiment II (section IV), the graphics program was used to occlude the participant's view of the road except for one second glimpses when requested through a key-press.

The driving simulator and shared-controller described in this section were used in three experiments. Experiment I (section III) defined a baseline measure of driving performance for participants with and without the haptic assist. In Experiment II (section IV), the participants' visual demand while driving was measured using the visual occlusion method with and without haptic assist. In Experiment III (section V), participants were asked to perform a secondary task while driving. Again, the experiment was run for the two conditions: with and without haptic assist, and the effect of haptic assist on secondary task performance was measured by accuracy and reaction time.

III. EXPERIMENT I (BASELINE)

The objective of our first experiment was to quantify the improvement in driving performance afforded by the haptic assist controller. Driving performance was defined in terms of two performance variables: lateral error in tracking the road centerline (a path following task), and the number of obstacles hit. The haptic assist, when present, could be entrusted to help only with path following. It was solely the driver's responsibility to avoid obstacles in the middle of the road—the automation had no information about the obstacles. Thus the obstacles provided the motivation for keeping the human in the loop. The experimental condition under investigation in Experiment I was simply the presence of haptic assist. Experiment I provided the baseline performance, against which the results from Experiments II and III were compared. Experiments II and III imposed additional experimental conditions under which the effects of haptic assist were measured.

A. Procedure I

1) Participants: : Eleven participants, 9 men and 2 women, between the ages of 20 and 63 (M=30, SD=11.9 years) volunteered for the study. All participants had normal or corrected-to-normal vision. Each participant provided informed consent in accordance with University of Michigan human subject protection policies. Individuals were not paid for their participation. Each participated in one experimental session lasting approximately one hour. Participants, whether left or right handed, were asked to use their right hand on the motorized steering wheel to steer the simulated vehicle along the centerline of the roadway as closely as possible without colliding with any obstacles. Each participant spent one five-minute trial familiarizing him or herself with the path following task under the experimental conditions of all three experiments.

2) Design: : After completing the practice trial, each participant completed six 5-minute trials, each representing a unique set of experimental conditions. Two of these six trials were designed to assess baseline path following performance: one trial without haptic assist and the other with haptic assist. Each participant was randomly assigned a sequence of trials chosen from a set designed to counterbalance the ordering of the haptic assist condition. Participants did not receive performance feedback at the end of trials, however the roadway and excursions of the car from the centerline were visible on the graphic display, and obstacle collisions, if they occurred, were accompanied by a brief flash of orange on the entire screen. The simulator logged the time, vehicle position and orientation, obstacle collisions, the closest point on the centerline (computed in real-time), and the torque displayed on the motorized steering wheel.

3) Dependent Variables and Data Analysis: : To assess driving performance, two performance measures were defined: one for path following and the other for obstacle avoidance. The shortest distance between the center of the car and the center of the road was computed at each sample time (every 8 ms) and defined as the lateral error (LE). The root-mean-square (RMS) of LE, denoted RMS[LE], was used to assess path following performance. However, to facilitate analysis of path following performance and its dependence on assist condition independent of the obstacle avoidance maneuvers, the data was partitioned into segments *between* obstacles and segments *near* obstacles. Partitioning was defined in time, where *near* indicates 2 seconds before and 1 second after the instant at which the closest point on the centerline passed the obstacle. The *near* data segments were then discarded from the measure of path following performance. Obstacle avoidance performance was defined as the fraction of obstacles hit from the 30 presented, reported as a percentage and denoted %Hit.

Quantile plots were used to verify that the data fit normal distributions for both performance metrics when considered across the 11 participants. Using $\alpha = 0.05$ to establish statistical significance of results, multiple-factor ANOVA was performed for the two dependent performance measures: RMS[LE] and %Hit.

B. Results I

Fig. 5 shows the tracking performance of a typical participant in a generic section of the roadway with and without steering assist. The section of roadway shown is 220 meters in length and took about 32 seconds to traverse at the constant 15 mph vehicle speed – a moderate pace given the curvature of the road. The top trace shows the curvature of the road, indicating that a left turn and two straight segments are represented in this section of roadway. Deviation from the centerline is graphed versus time in the lower two traces, where trace (A) was recorded without haptic assist and trace (B) was recorded with haptic assist. The obstacles are outlined as circles of radius 1.6 m, but appear as ellipses due to the non-unity aspect ratio. The 1.6 m radius accounts for the 0.7 m obstacle radius and 0.9 m car half-width: that is, a collision occurs if the vehicle center comes within 1.6 meters of an obstacle center. Obstacle avoidance maneuvers produced by the participant are apparent in both traces, and those maneuvers are not appreciably different by condition. However, differences across condition are apparent in tracking performance in the sections of roadway between obstacles. Improvement can be observed in trace (B), where haptic steering assist was provided.

As previously described in section III-A.3, the data was partitioned into segments either *near* or *between* obstacles, and only values of LE sampled when the vehicle was considered *between* obstacles were used to calculate RMS[LE]. The shaded areas in Fig. 5 indicate data within the 3 second windows around each obstacle, which were considered *near*.

There was some variation in driving behavior among participants, particularly in the obstacle avoidance maneuvers. Some drivers chose more “aggressive” driving styles; they would wait longer before avoiding an obstacle and they would turn the steering wheel faster and with more effort. The variation across all participants is shown as point-wise percentiles in Fig. 6 over the same section of road shown in Fig. 5. After computing point-wise percentiles, the data was low-pass filtered with a non-causal second-order Butterworth filter with a spatial cuttoff frequency of 3.7 m^{-1}. The 5^{th} and 95^{th} percentile of $|LE|$ form the bottom and top edges of the shaded region in the plot. The dark line drawn through the shaded region is the point-wise median of $|LE|$ for all participants. Qualitatively, the plot shows that the obstacle avoidance behavior is not significantly altered by the haptic assist, but the tracking error is reduced in the sections between obstacles.

Multiple factor ANOVA applied to RMS[LE] revealed significant main effects due to the assist condition, $\mathrm{F}(1,21) = 4.9$, $p = 0.05$, MSE $= 0.15$, and subject, $\mathrm{F}(10,21) = 3.5$, $p = 0.03$, MSE $= 0.11$. For %Hit, again a significant main effect due to assist condition was found, $\mathrm{F}(1,21) = 9.4$, $p = 0.01$, MSE $= 0.0032$, however no significant main effect was found for subject, $\mathrm{F}(10,21) = 2.4$, $p = 0.09$, MSE $= 0.0083$.

Thereafter, a paired t-test analysis was applied to the data. Table I presents the sample mean $\bar{x}$ and standard deviation s of RMS[LE] and %Hit along with the paired t-tests results. For both performance measures, the difference between the *no-assist* and the *with-assist* condition was calculated per subject, and the difference of means $\Delta\bar{x}$ and the standard deviation s_Δ of these differences along with the p-value and degrees-of-freedom (DOF) of the t-tests are presented in Table I. There was a 30% reduction in RMS[LE], $p = 0.013$, $t(10)$. However, for %Hit, there was a statistically significant increase from 0.57% to 2.8%, p=.0059, t(10), when haptic assist was added. This result represents a cost of adding haptic assist rather than a benefit. Note, however, that the assist is always trying to drive the vehicle back to the center of the road, exactly where the obstacles are placed. Without driver intervention, the car would drive through every obstacle on the course.

IV. EXPERIMENT II (VISUAL DEMAND)

Our second experiment aimed to quantify the ability of the haptic assist controller to reduce the demand for visual cues while aiding participants in the path following task. Again, because of the presence of obstacles on the road centerline, the path following task demanded a certain amount of attention from the participants, whether or not the haptic assist was present. As in Experiment I, the independent variable is the presence of haptic assist. In Experiment II, however, the effects of haptic assist were measured with reduced visual feedback. The graphical display was blank except when a visual refresh was requested by the participant. The requests for visual feedback provided a measure of the partipants' instantaneous and average demand for visual cues.

A. Procedure II

1) Participants: : The same eleven individuals who participated in Experiment I also participated in Experiment II.

2) Design: : Two of the six trials pertained to Experiment II. These two trials, one with and one without haptic assist, were designed to assess driving performance and visual demand while the visual feedback was metered according to the visual occlusion method [Tsimhoni and Green, 2001]. To measure the participants' demand for visual cues, the graphical display of the driving environment and roadway was blank except for one-second glimpses provided each time participants pressed a key with their left hand on the computer keyboard. Participants were instructed to request the display whenever they felt that additional visual feedback was necessary to follow the roadway and avoid obstacles. A measure of visual demand throughout the trial was measured by the fraction of time that the visual feedback was not occluded. In addition to the data logged in Experiment I, the simulator logged key-presses on the keyboard.

3) Dependent Variables and Data Analysis: : To assess driving performance, the same two performance metrics already defined for Experiment I were used: RMS[LE] (defined in regions away from obstacles) and %Hit. In addition, an instantaneous measure of visual demand was computed using

$$\text{VisD} = \frac{1.0}{t_i - t_{i-1}} \tag{1}$$

where t_i is the time of the i^{th} key press and the numerator is the period of the time that the display was not occluded per request [Tsimhoni and Green, 2001]. A measure of average visual demand over the entire trial, denoted Avg[VisD], was computed by the number of key-presses in a given trial divided by the duration of the trial (300 seconds).

Data analysis included quantile pots, multiple-factor ANOVA, and t-tests. The value $\alpha = 0.05$ was used to establish statistical significance.

B. Results II

The three performance metrics for Experiment II (Visual Demand) were: RMS[LE], %Hit, and Avg[VisD]. Multiple-factor ANOVA was performed for all three dependent performance measures. Analysis of RMS[LE] revealed significant main effects due to assist condition, F$(1, 21) = 12$, $p = 0.005$, MSE$= 0.65$, and subject, F$(10, 21) = 4.5$, $p = 0.01$, MSE$= 0.23$. For %Hit, neither assist condition nor subject were significant main effects, although assist condition approached significance, F$(1, 21) = 3.5$, $p = 0.09$, MSE$= 0.011$. The new performance measure in this experiment was Avg[VisD] and the ANOVA results indicated significant main effects for assist condition, F$(1, 21) = 96$, $p = 0.0001$, MSE$= 1370$, and for subject, F$(10, 21) = 8.6$, $p = 0.001$, MSE$= 1220$.

As in Experiment I, the presence of haptic assist produced a reduction in RMS[LE] in regions away from obstacles. The data presented in Figures 5 and 6 from Experiment I are also representative of the effects of the assist condition on path following for Experiment II. Similarly, there was an increase in %Hit, however, in Experiment II, the increase was not a statistically significant result. Visual demand was significantly reduced with the addition of haptic assist.

When Avg[VisD] is plotted against path length, there is no obvious, qualitative correlation with the proximity to obstacles or curves. In fact, visual demand remains relatively constant over the entire course. We conjectured that participants might try to schedule their request for a visual refresh during critical periods (e.g. a short time before an obstacle), in which case the key-press frequency would be a poor measure of visual demand. However, a histogram of the number of key presses in relation to time before and after passing an obstacle revealed a flat distribution.

To further investigate the dependence of RMS[LE], %Hit, and Avg[VisD] on assist condition, paired t-tests were applied. Table II presents the sample mean $\bar{x}$ and standard deviation s of the RMS[LE], %Hit, and Avg[VisD], along with the mean differences $\Delta\bar{x}$ by condition and associated standard deviation s_Δ and p-values resulting from the paired t-tests. There was a significant reduction in RMS[LE] of 41%, $p = 0.002$, $t(10)$, and a significant reduction in Avg[VisD] of 29%, $p = 0.0001$, $t(10)$, when the haptic assist was available compared to the no-assist condition. With assist added, %Hit increased from 1.8% to 6.4%, and the increase in %Hit across the haptic assist condition is again significant, $p = 0.045$, $t(10)$. Fig. 7 shows a boxplot of the average visual demand Avg[VisD] by assist condition, where each box represents n=11 participants. As evident in the figure, the median visual demand is lower when the haptic assist is turned on.

V. EXPERIMENT III (SECONDARY TASK)

The third experiment was aimed at quantifying the ability of the haptic assist steering wheel to aid the participant in a path following task while reducing mental load in spatial processing. Mental processing load was estimated by measuring performance on a secondary task that required the participant to localize tones emitted from three speakers. Tone localization was chosen as a secondary task on the assumption that it would interfere with the path following task or it would compete for the same spatial processing code [Wickens and Liu, 1988]. Also, the ability to localize sounds, including reaction times for localization from within a vehicle, can be critical to safety and overall driving performance [Wallace and Fisher, 1998].

A. Procedure III

1) Participants: : The same 11 individuals who participated in Experiments I & II also participated in Experiment III. Subjects were screened for normal, balanced hearing per self-assessment.

2) Design: : Two of the six trials performed by each subject pertained to Experiment III, one each for the two haptic assist conditions. These two trials were designed to simultaneously assess driving performance and performance on a secondary task involving auditory localization of tones. The primary task was the same as in Experiments I & II: to follow the center of the road as closely as possible while avoiding obstacles. Participants were not told which task was more important nor how their performance on either task would be measured.

3) Secondary Task: Tone Location: : Three computer speakers were placed approximately 1 m in front of the participant's head with a 18 cm center-to-center spacing on top of the computer monitor that displayed the simulated roadway. These speakers played half-second square-wave tones with a fundamental frequency of middle-C. The sound-level reading at the participant's head location was measured to be 81 dBA. The time between tones was randomly selected with a uniform distribution between 2 and 6 seconds. Participants were asked to identify which of the three speakers played the tone and to press a corresponding key on the computer keyboard. The key 'j' was used by the participant to indicate that the left speaker had played, the 'k' key to indicate the center speaker, and the 'l' key to indicate the right speaker. Participants were not told that the speed of their response would be measured.

Performance by each participant on both the primary and secondary tasks was recorded for two 5-minute trials: one trial without haptic assist and the other trial with haptic assist. The simulator logged the time, the vehicle position and orientation, the closest point on the centerline, the number of obstacles hit, the torque displayed on the motorized steering wheel, the tones sounded by the speakers, and the key-presses registered by the keyboard.

4) Dependent Variables and Data Analysis: :

To assess driving performance, the same two performance metrics defined for Experiment I were used: RMS[LE] (in regions away from obstacles) and %Hit. These performance metrics were analyzed as described above for Experiment I.

Two additional performance metrics were defined for the secondary tone location task: accuracy and reaction time. Accuracy, denoted ToneAcc was defined as the percentage of tones that were correctly identified. The reaction time, denoted RT, was the time, in ms, between the tone onset and the registration of the key press by the personal computer. Because of technical limitations, RT data were quantized to 8 millisecond levels. The precision of the timing, however, was better than 1 microsecond, and timing jitter (standard deviation of sample time) was measured at 0.53 ms. Quantization and timing jitter can be considered noise in the measurements of response time. Data analysis for the various performance metrics included quantile pots, multiple-factor ANOVA, and t-tests. The value $\alpha = 0.05$ was used to establish statistical significance.

ToneAcc performance was first determined independently for each speaker by computing the percentage of correct responses for a particular speaker (Left, Center, or Right). For example, the location accuracy for the left speaker is the number of times the ‘j’ key was hit in response to a tone from the left speaker as a percentage of the total number of tones from the left speaker during the 5-minute trial (about 37 tones). Quantile plots of the tone location accuracy data showed that these data were approximately normally distributed. ANOVA showed that the speaker (Right, Center, Left) was not a significant main effect. Thus the data by speaker were combined to define a single ToneAcc performance metric for each subject and assist condition.

Quantile plots were also used to check for normality of the (RT) data. The RT data were, as expected, not normally distributed, so the use of transformations and data set truncations were investigated. The inverse (1/RT) transformation, the logarithmic (log(RT)) transformation, and truncations of the RT data to 0.75, 1.0, 1.25, 1.5 and 2.0 seconds were applied to the data, where truncation refers to exclusion of all data beyond the range specified. The influence of these various transformations and truncations on the ANOVA-reported p-values were compared to the influence of the same operations on the p-values generated by synthesized data as reported in [Ratcliff, 1993]. Data were synthesized in [Ratcliff, 1993] by specifying a difference in means or tail sizes between two ex-Gaussian distributions. A comparison of p-value trends produced by the operations on our data versus the operations on the synthesized data suggested that a 1.25 second cutoff produced the most statistical power, and suggested further that our data showed a difference in tail sizes. The rationale behind truncation is that the longer RT data are spurious in the sense that they are strongly influenced by processes other than the condition being tested, such as distractions or intrusion of cognitive processes not relevant to the experiment [Ulrich and Miller, 1994]. Despite quantization of timing data, the high precision of the timing data and low software jitter allows the mean difference to be extracted with precision similar to the jitter (+/-0.5 ms). Note that each of the 11 participants reacted to 112 tones in each trial.

B. *Results III*

As in Experiments I & II, the presence of haptic assist produced a reduction in RMS[LE] in regions away from obstacles. The data presented in Figures 5 and 6 for Experiment I above are also representative of the effects of the assist condition on path following performance for Experiment III.

Multiple-factor ANOVA applied to RMS[LE] revealed significant main effects due to assist condition, $\mathrm{F}(1, 21) = 8.78$, $p = 0.014$, MSE$= 0.347$, and subject, $\mathrm{F}(10, 21) = 3.4$, $p = 0.033$, MSE$= 0.134$. For %Hit, assist condition was not a significant main effect, but subject was a main effect, $\mathrm{F}(1, 21) = 5.07$, $p = 0.0085$, MSE$= 0.00682$.

The sample mean $\bar{x}$ and standard deviation s (collapsed across participants) of RMS[LE], %Hit, and ToneAcc are presented in Table III, along with the p-values of paired t-tests applied to the difference in the means $\Delta\bar{x}$. There was a significant 38% reduction in RMS[LE], p<0.0093, t(10). That is, path following was significantly improved in the regions between obstacles with the addition of haptic assist. The percentage of obstacles hit increased from 3.4% to 4.3%, but the difference was not statistically significant. Of the two new performance metrics that measured performance on the secondary (tone localization) task, ToneAcc did not change appreciably. The difference in mean percentage of correct identifications rose slightly with the addition of haptic assist, however without any statistical significance, p=.604, t(10).

RT was the other performance metric for the secondary task. After a multiple-factor ANOVA revealed that the effect of path curvature on the RT data was not a significant main effect, $\mathrm{F}(1, 2242) = 0.21$, a multiple-factor ANOVA was performed considering assist condition and proximity to obstacles (near/between) as experimental factors. The ANOVA reported significant main effects in haptic assist condition, $\mathrm{F}(1, 2286) = 8.5$, $p = 0.003$, MSE$= 0.16$, proximity to obstacles, $\mathrm{F}(1, 2286) = 35$, $p = 0.0001$, MSE$= 0.66$, and subject, $\mathrm{F}(10, 2286) = 52$, $p = 0.0001$, MSE$= 0.97$, with significant interactions in assist by subject, $\mathrm{F}(10, 2286) = 0.12$, $p = 0.0001$, MSE$= 0.12$, and in proximity to obstacles by subject, $\mathrm{F}(10, 2286) = 3.2$, $p = 0.0005$, MSE$= 0.059$.

A paired t-test was performed for the RT data, subtracting subjects' mean reaction-time from their respective RT data, and comparing the population means with and without haptic assist. A statistically significant 18 ms decrease in RT was found with haptic assist compared to no assist, p=0.0009, t(2328), regardless of proximity to obstacles. When only considering RT data between obstacles, the effect of adding haptic assist was a 21 ms decrease in RT, p=0.0005, t(1612), and considering RT data only near obstacles, the effect of adding haptic assist was a 10 ms increase in RT, however without statistical significance, p=0.172, t(714). Because proximity to obstacles was a main effect, we determined the effect of proximity to obstacles without regard to assist condition, and the mean reaction time was found to increase by 37 ms when participants were near obstacles.

VI. GENERAL DISCUSSION

The data from all three experiments may be examined to compare the effects of haptic assist to the effects of imposing the conditions of the visual occlusion method and of adding a secondary task. Fig. 8 shows 6 boxplots defined by the medians and upper and lower quartiles for the two assist conditions (on/off) and by the three experiments (I-Baseline, II-Visual Demand, and III-Secondary Task). The improvement in path following performance afforded by the haptic assist is evident in each experiment. The cost in path following performance incurred by the conditions of the visual occlusion method and the addition of a secondary task are also evident when comparing across experiment. While the availability of haptic assist does not restore path following performance to baseline levels under visual occlusion, haptic assist does restore path following performance to baseline performance with haptic assist under the secondary task. These data show that haptic assist can improve path following performance to a degree that does not diminish even when a secondary task is added.

To achieve path-following, the stiffness of the shared-controller must be tuned to balance two conflicting goals. The automation must resist deviations from its desired steering angle with enough authority to reject disturbances such as wind gusts and road crown. The automation effectively resists undesired movement of the steering wheel by constructing a virtual spring to hold the wheel. A greater spring stiffness achieves the tracking goals better. However, in sharing control, the driver must overcome the stiffness presented by the virtual spring if he wishes to steer with an angle other than that determined by the automation. If the virtual spring is too stiff, the driver may find it difficult to over-power the controller's actions, but if the spring is very weak, disturbances would cause excessive error in lane-keeping with the controller acting alone.

As discussed under the results headings in each of the experiments above, the improvement in the path following performance was usually accompanied by reduced obstacle avoidance performance (increased %Hit). Fig. 9 shows the number of obstacles hit for the two assist conditions (on/off) for each of the three experiments. A marker for each participant indicates the number of obstacles hit in each of the six trials, arranged by assist condition and experiment. The dependance of the number of obstacles hit on the participant is evident. The reduction in obstacle avoidance performance with the addition of assist is clear, especially in Experiments I and II. Note, however, that a reduction in performance is a natural consequence of an assist system that helps maintain path following but is not aware of obstacles that lie on the path. Note also that the decrement in performance incurred by the haptic assist is about the same magnitude as the decrement incurred by the addition of a secondary task. Also, in the presence of the secondary task, the addition of haptic assist does not incur a statistically significant further performance cost in obstacle avoidance. These results, however, are somewhat inconclusive. They merit further exploration in future studies.

Certainly the reduction in the obstacle avoidance performance incurred by haptic assist motivates the development of sensors in the automobile that can serve in collision warning or collision avoidance systems. The assist could be turned off and a warning (audio, visual, or haptic) sounded when an obstacle is detected by the automatic controller. A more proactive system would assess the traffic situation and help the driver make an evasive maneuver by planning a path around the obstacle.

Accuracy and reaction time were the metrics of participants' performance in the tone location experiment. The hypothesis of Experiment III was that the performance of the secondary task would improve if the driver was provided haptic assist. Indeed, there was an improvement (reduction) of the reaction time by 18 ms,p=0.0009, t(2328), but the improvement in the localization accuracy was small and not statistically significant. The reduction in reaction time is a desirable result for two reasons. Taken by itself, a faster reaction means that the driver can react sooner to dangerous situations—for example, reacting to the honk of a horn from another vehicle. The faster reaction time to the auditory probe also implies that, with shared control, the driver experiences a reduced cognitive load in the driving task [Raney, 1993]. The validity of using reaction time as an indicator of cognitive load was affirmed by the 37 millisecond increase in reaction time when participants were near obstacles (actively engaged in obstacle avoidance) versus far from obstacles, $p<0.0001$, t(2328). So in addition to the improved performance in the primary control task, the haptic assist evidently increases the availability of cognitive processing capacity for the performance of a secondary task.

The presence of the secondary task decreased the path following performance by 18%, when compared with the baseline experiment with no assist, p=0.033, t(10). This statistic is further evidence that the spatial reasoning task selected for the secondary task was competing for some of the same cognitive processing capacity required for driving (the primary task). When haptic assist was enabled and the path following performance of the baseline was compared with the path following in the presence of the secondary task, there was only a 6% degradation in performance, which was not statistically significant, p=0.64, t(10). This result suggests that the haptic assist can allow a driver to perform a secondary task with negligible degradation in tracking performance.

VII. SUMMARY

We have investigated the use of haptic interface to realize and test the idea of a human driver sharing control of vehicle heading with an automatic controller. The human and controller share the same control interface (e.g. steering wheel) and are mechanically interconnected such that they may exchange information and share control authority with one another. Haptic display becomes the means to place the automatic controller in the haptic perceptual space of the human. The human is free to only observe the actions of the controller but may over-ride them at any time he sees fit, based on his perception of additional factors in the task environment. Shared control extends the notion of a virtual fixture to a virtual agent or co-pilot. Like the virtual fixture, the human is aware of the virtual agent by feel and can use the agent to negotiate a task more efficiently.

While certain recommendations about haptic versus other types of assist remain unexplored in our present experiments, our findings hold some important implications for the design of automation systems. We demonstrated a significant reduction in visual demand and a freeing of attention by inserting automation into the control loop through a motor on the manual interface. Both of these positive effects were achieved while significantly improving performance on the primary driving task, which was shared by the human/machine team. Through the use of haptic assist, the human remains in-the-loop and so we believe that shared control through a haptic interface incurs minimal loss of obstacle avoidance performance to surprise events in the primary task.

We hypothesize that the mechanical coupling between hand and manual interface and the co-located sensing and actuation functions of the hand keep the operator in-the-loop. Thus we expected to measure maintained obstacle avoidance, but this expectation was not fully borne out in our data. There was a statistically significant reduction in the obstacle avoidance measured with the addition of haptic assist. But this should be considered in light of the fact that our measure of obstacle avoidance was strongly confounded with the haptic assist condition. Specifically, the haptic assist favored the center of the path where the obstacles were located. This condition was most apparent in the baseline trial, without the conditions of visual occlusion or the presence of a secondary task. Notably, under the visual occlusion and secondary task conditions, the diminished obstacle avoidance performance incurred by the automation disappeared.

The methods and experiments described in this paper both draw from and contribute to the fields of human factors and haptic interface. In the field of human factors, there already exists substantial knowledge about the effects of adding automation on the performance of human-machine teams. However, the use of haptic feedback and its relative merit compared to visual or auditory feedback has not been evaluated for control sharing. In particular, haptic feedback can be used to provide information regarding control action taken by an automation system that does not further load the visual or auditory systems. In this paper we have demonstrated improved performance with the addition of automation while actually reducing visual demand. In the field of haptic interface, the ability of a manual interface to simultaneously display information while functioning as a control input device is well understood and used to advantage in numerous applications. However, only the primary task performance benefits of adding automation with haptic feedback have received attention in the field of haptic interface. The auxiliary performance benefits of haptic assist, either in the reduction of a particular mental workload (e.g. spatial processing) or reduction in demand on other perceptual systems, are often sought in applications and sometimes claimed, but seldom quantified. Our work combines the concepts of co-located action and sensing inherent to haptic interfaces and examines not only the human-machine performance in the primary task but also human performance in a secondary task.

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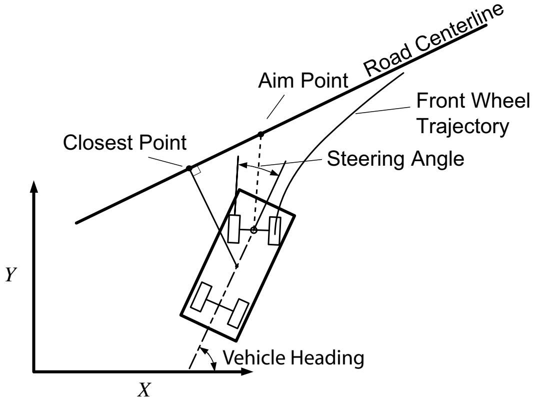

Fig. 2. The automation turns the front wheels of the vehicle towards an aim-point. This point remains a fixed distance (10 m) ahead of the vehicle as measured along the road centerline.

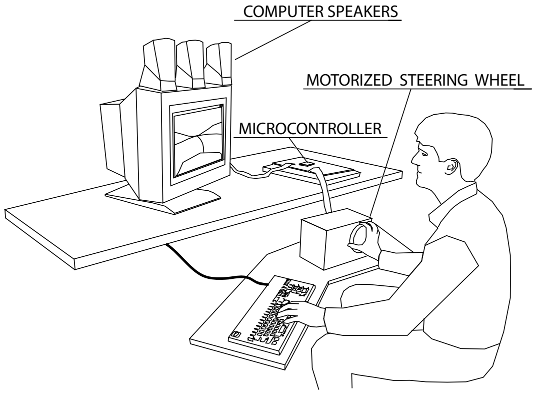

Fig. 3. A participant has one hand on the motorized steering wheel while viewing the animated roadway on the computer monitor. The left hand on the keyboard requests visual display in Experiment II and responds to tones from the speakers atop the monitor in Experiment III.

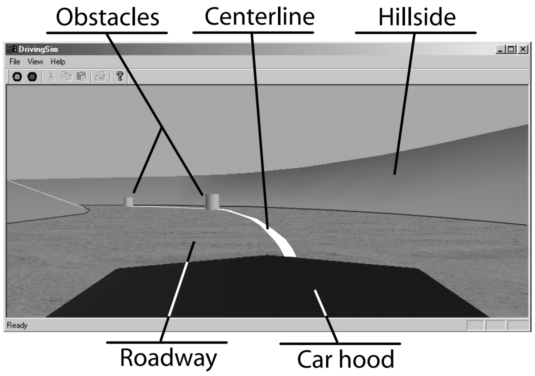

Fig. 4. An OpenGL animation of the roadway visible over the hood provided subjects with visual feedback (labels added).

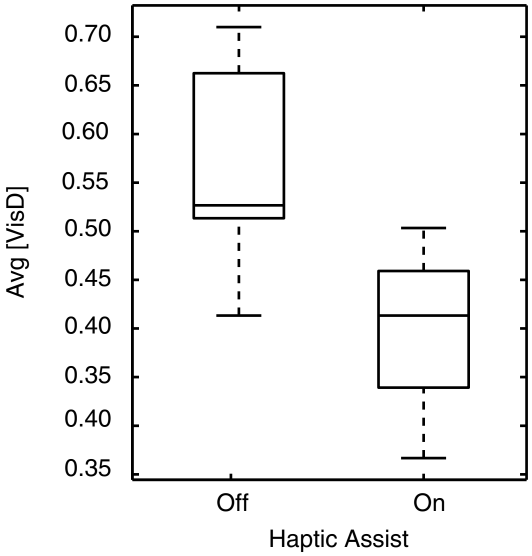

Fig. 7. Boxplot of Avg[VisD] by assist condition

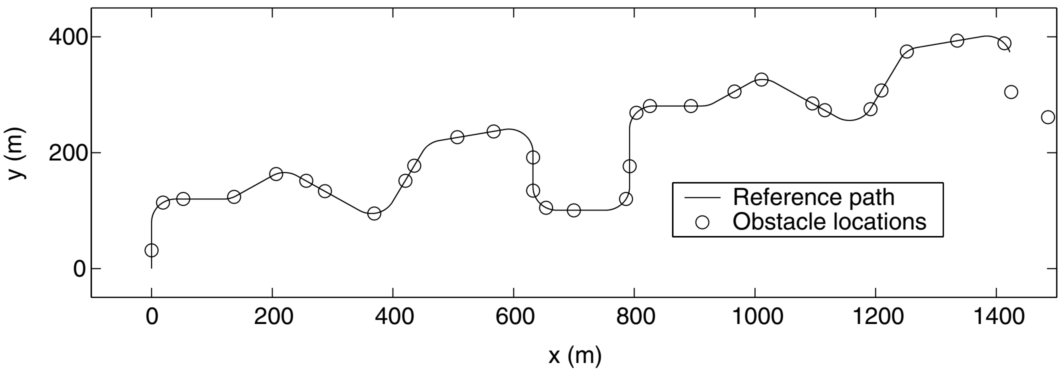

Fig. 1. A top-down view of the driving course that participants traversed during each trial. The location of obstacles along the road centerline is indicated with circles.

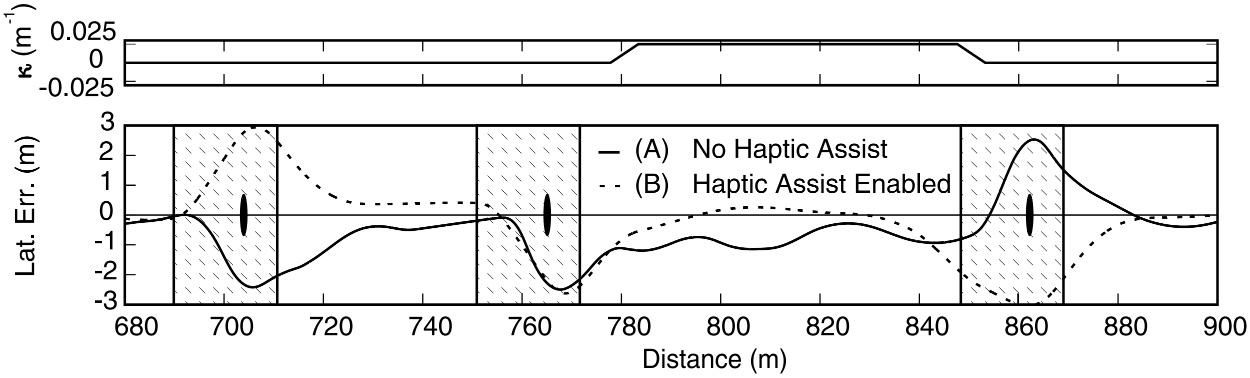

Fig. 5. Plot of one participant's lateral deviation over a 220 m section of roadway under conditions (A) without steering assist and (B) with steering assist. The top trace indicates roadway curvature and the ellipses in the lower plot show the size and location of obstacles. The shaded regions indicate segments omitted from the path following performance metric, RMS[LE].

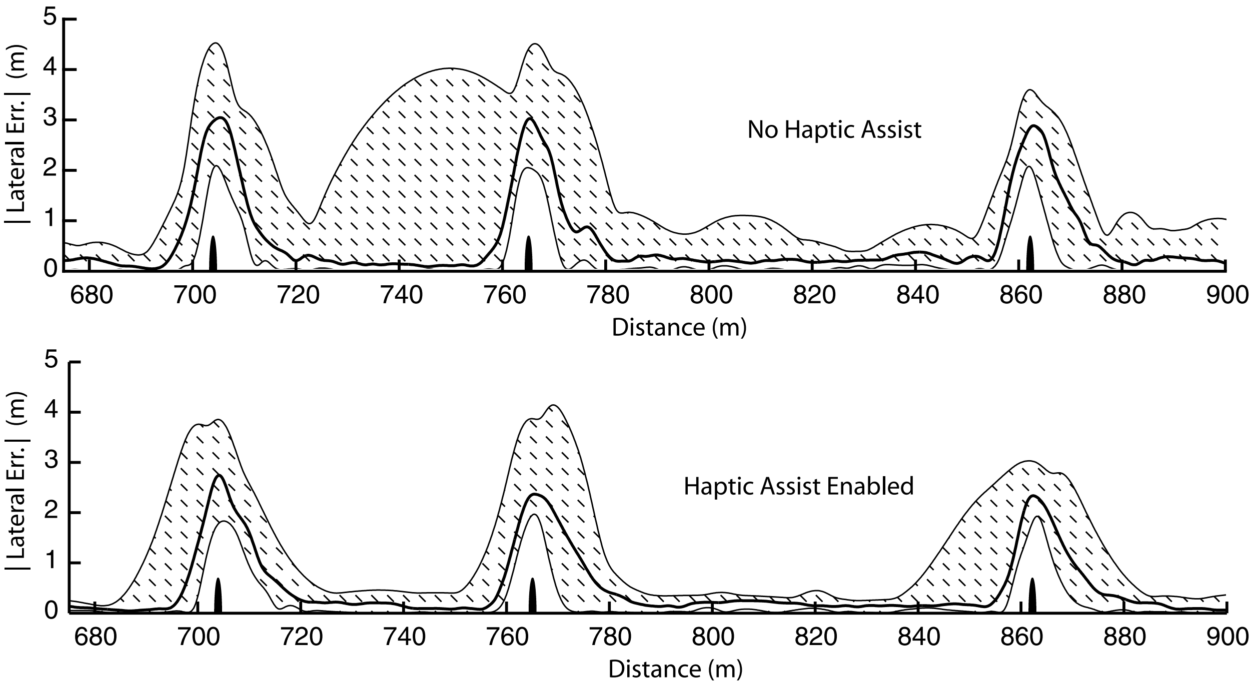

Fig. 6. Two plots shade the 5 to 95 percentile-intervals for the absolute value of the lateral error data without haptic assist and with haptic assist. The line running through the shaded region indicates the 50th percentile. The portion of the course shown includes three obstacles shown as half ellipses.

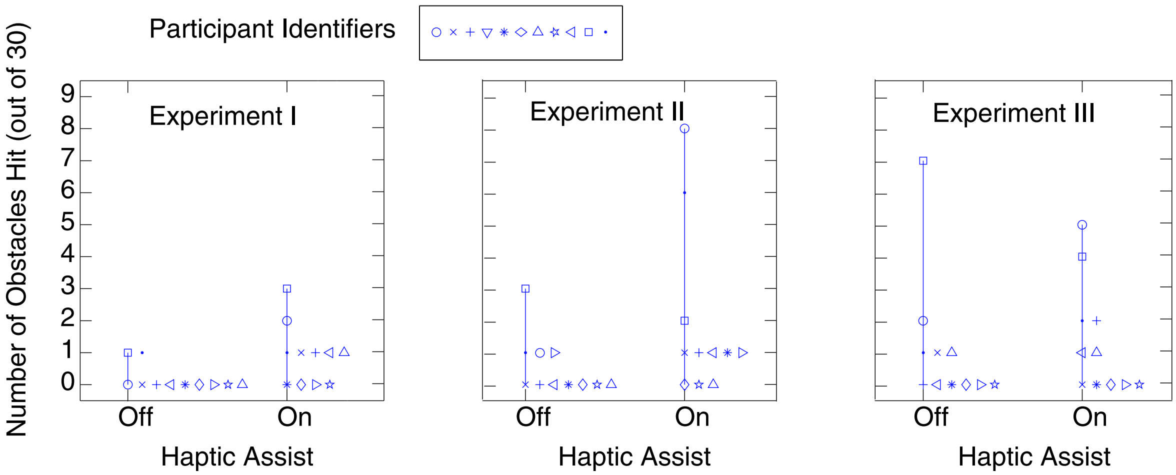

Fig. 9. Plots of the number of obstacles hit for each participant are shown for the two assist conditions and the three experiments.

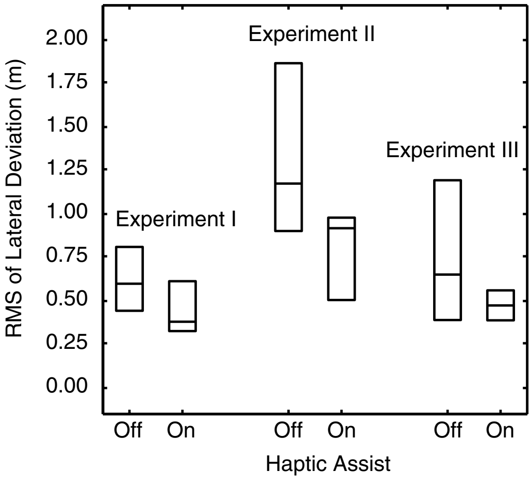

Fig. 8. Box-plots of RMS[LE], showing medians and quartiles for the two assist conditions and the three experiments.

TABLE I

Mean and standard deviation of RMS[LE] and %Hit for the baseline trials with and without assist.

Performance Metric	No Assist		With Assist		Paired t-Test			
	$\bar{x}$	s	$\bar{x}$	s	$\Delta\bar{x}$	s_Δ	p	DOF
RMS[LE] (m)	0.680	0.391	0.473	0.234	-0.207	0.264	0.0134	10
%Hit (%)	0.61	1.26	3.03	3.15	+2.42	2.62	0.00594	10

TABLE II

Mean and standard deviation of RMS[LE], %Hit, and Avg[VisD] for Experiment II.

Performance Metric	No Assist		With Assist		Paired t-Test			
	$\bar{x}$	s	$\bar{x}$	s	$\Delta\bar{x}$	s_Δ	p	DOF
RMS[LE] (m)	1.412	0.727	0.828	0.312	-0.584	0.513	0.0018	10
%Hit (%)	1.82	3.11	6.36	8.75	+4.54	8.07	0.0456	10
Avg[VisD] (-)	0.570	0.0966	0.404	0.0765	-0.166	0.0563	< 0.0001	10

TABLE III

Mean and standard deviation of RMS[LE], %Hit, ToneAcc and RT for Experiment III.

Performance Metric	No Assist		With Assist		Paired t-Test			
	$\bar{x}$	s	$\bar{x}$	s	$\Delta\bar{x}$	s_Δ	p	DOF
RMS[LE] (m)	0.817	0.520	0.503	0.221	-0.314	0.264	0.0093	10
%Hit (%)	3.64	6.90	4.55	5.83	+0.91	5.18	0.287	10
ToneAcc (%)	94.9	4.41	95.3	3.92	+0.35	4.29	0.604	10
RT (ms)	564	147	545	132	-18.2	143	0.0009	2318