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MITIGATING THE EFFECTS OF TIME LAG ON DRIVING PERFORMANCE

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ABSTRACT

Time lags are known to reduce performance in human-in-the-loop control systems. Performance decrements for human-in-the-loop control systems as a result of time lags are generally associated with the operator's inability to predict the outcome of their control input and are dependent upon the characteristics of the lag (e.g., magnitude and variability). Further, the effects of variable time lags are not well studied or understood, but may exacerbate the effects on human control actions observed with fixed lags. Several studies have demonstrated mechanisms that can help combat the effects of lag including adaptation, mathematical predictors (e.g., filters), and predictive displays. This experiment examined the effects of lag and lag variability on a simulated driving task, as well as a possible mitigation (predictive display) for the effects of lag. Results indicated that lag variability significantly reduced driving performance, and that the predictive display significantly improved performance for both fixed and variable lags.

INTRODUCTION

The effects of time lag have been studied since the 1950s [2-6], with interest first sparked by the prospects of space travel and remote operations from the earth. Lag is defined as the time delay between the user's input and the system's displayed response, usually caused by the communication delays inherent in the control system [1]. Lag is inherent in drive-by-wire/remote driving tasks, resulting from deficiencies in the communication medium/methods (e.g., bandwidth limitations, graphical rendering and computation requirements) between the operator and asset [2]. As a result, the visual/control feedback to the operator often lags behind the real-time feedback from the actual environment and control inputs[1]. For human in-the-loop control systems, lag has been demonstrated to affect performance factors, mainly the speed and accuracy of the control actions of human operators. Performance decrements as a result of time lag are generally a result of the operator's inability to predict the outcome of their control input. The magnitude of the lag has an effect on the extent of the performance degradation [3-5;7;8].

There are several mechanisms that can help humans cope with time lags in human-in-the-loop control systems including adaptation, mathematical predictors and predictive displays. Cunningham et al. [3] demonstrated that humans can adapt to a lag of 230 ms in less than 30 minutes (min) and that this adaptation could be generalized across different driving virtual environments (VEs). Adaptation, however, is dependent on the magnitude (and variability) of the lag, as adaptation to temporal misalignments are dependent on the human's ability to predict the outcome of their control inputs [4]. When time delay between control input and output exceed the human's ability to predict the outcome of control inputs, it often leads to a 'move and wait' approach where a command is input into the system and the operator waits for the system to respond [5].

Several studies have also demonstrated the effectiveness of mathematical filters (e.g., Kalman Filter Predictors [6] and Smith Predictors [7]) to help combat the effects of lag, by using past and current states of the system to estimate future states of the system. Though mathematical filters have been used to mitigate the effects of lag in robotic assets [8], their utility in human controlled assets are unclear.

Predictive displays have also been used to help offset the effects of time delays by providing almost immediate feedback to the operator via model representation. A model of the system that predicts the consequences of control inputs is presented on a display so that operators do not have to perform such prediction themselves [9;10]. Predictive displays have been demonstrated to increase performance in telemanipulation and teleoperation tasks with time delays [9;11-13].

Though there has been much research on the effects of time lags on performance, most of it has focused on fixed

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[1] The temporal responsiveness of control inputs can also be affected by control algorithms; however, that was not the focus of this effort.

time delays. Very few studies have examined the effects of lag variability on performance for human-in-the-loop control systems. One such study [14], suggested that variable lag was associated with negative performance as compared to fixed lag for a teleoperation task. However, a possible speed-accuracy tradeoff reduced the strength of this assertion, warranting further investigation into the effects of variable lag on performance.

This experiment examined the effects of both fixed and variable lag on a drive-by-wire/remote driving task. This experiment also extended on previous research regarding lag mitigation by examining the effects of a predictive display on both fixed and variable lag. It was hypothesized that variable lag would be associated with worse driving performance than fixed lag on a drive-by-wire/remote driving task. It was also hypothesized that the predictive display would improve driving performance for both fixed and variable lag.

PROCEDURES

Participants

Twelve civilians (8 male, 4 female) with an average age of 34.3 ± 2.5[2] years participated in this experiment. One participant was excused from completing the entire test after experience severe motion sickness symptoms.

Apparatus

The simulator used in this experiment was a fixed-base driver's station with three flat screen computer monitors (providing a field-of-view of 120° from display face to display face) and a driver control system that consists of a steering wheel, foot-brake, and accelerator (Figure 1A, inset). The computer-generated road-scene graphics were created using MINI-SIM by Real-Time technologies, Inc. The computer-generated test entailed several maneuvers including lane changes, sharp turns and slaloms (Figure 1B). The participants controlled a simulation of a High Mobility Multi-purpose Wheeled Vehicle (HMMWV).

The predictive display consisted of a semi-transparent image of the simulated HMMWV (e.g. 'ghost') superimposed over the simulated environment (Figure 1A). The simulated environment was representative of a hood-mounted video feed from a camera-based driving system. The semi-transparent image responded 'almost' immediately (70 ms) to the controller input of the participants, while the movement of the simulated environment responded with the designated time delay (see *Methods* section for the designated time delays). This predictive display was designed to account for: (1) the visual lag between video camera and video display and (2) the controller lag between control input and visual response feed associated with drive-by-wire/remote driving systems. This predictive display was conceptualized on the premise that as long as the relative position of the vehicle and the lag characteristics of the drive-by-wire/remote control system can be estimated, it is possible to create a semi-transparent marker on the video feed that represents the relative position of the vehicle in the environment in real time.

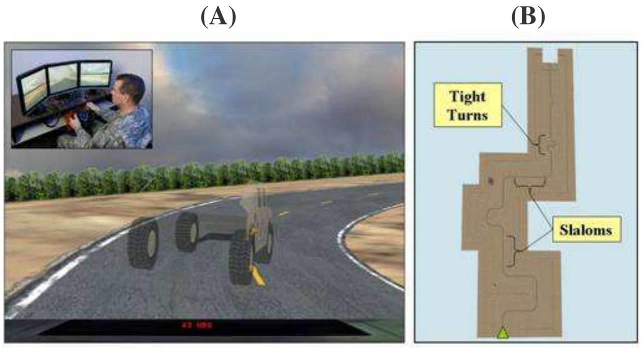

Figure 1. (A) Fixed-base driving simulator (inset) with predictive display, (B) Driving course

Methodology

The experimental design for this experiment was a 2x2 factorial design. The two independent variables were lag type and mitigation type. Lag type referred to either fixed or variable lag. The fixed lag had a mean of 700 ms (includes both 70 ms inherent lag and 630 ms additional lag). The variable lag was created using multiple sine waves and had a mean of 700 ms and varied between 400 and 1100 ms. Mitigation type referred to driving either with or without the predictive display. Thus, there were four conditions (Fixed/Mitigation, Fixed/No Mitigation, Variable/Mitigation, and Variable/No Mitigation). The order of condition presentation was counterbalanced between participants.

Pilot testing revealed that driver's performance generally plateaued within 1-2 driving trials. Consequently participants were asked to complete three driving trials within each of the four driving conditions[3]. Each driving trial consisted of the participant driving the simulated HMMWV along a ~4 kilometer (km) simulated path and lasted between 4-7 min depending on their speed.

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[2] All average values will be presented along with their standard error in the following form: Mean ± Standard Error.

[3] Since a majority of the participants' driving performance plateaued within the 1st driving trial, all trials were included in the data analyses, along with a factor to examine order effects.

Participants controlled both the direction and speed of the simulated vehicle. Driving performance measures included lane offset and vehicle speed. Lane offset was defined as deviation of the center of gravity of the simulated HMMWV from center of right lane.

RESULTS

Lane Offset

A mixed linear model revealed a significant interaction between lag type and mitigation type ($p < 0.03$, $F_{1,\ 110} = 5.4$) for average lane offset. When the mitigation was present, lane offset remained relatively low regardless of lag type; however, with no mitigation, lane offset was greater in variable lag conditions – Figure 2A. Although this effect can be explained simply by the interaction, lane offset was significantly greater when there was no mitigation (1.57 ± 0.06 m) than when the mitigation was present (1.20 ± 0.06 m), which is orthogonal to the interaction. There was no order effect associated for average lane offset.

There was also an interaction between lag type and mitigation type ($p < 0.03$, $F_{1,\ 112} = 5.172$) for the standard deviation (SD) in lane offset. When the lag was fixed, the SD in lane offset was relatively the same with and without the mitigation; however, when the lag was variable, the SD in lane offset was greatest when no mitigation was present (see Figure 2B). There was no order effect associated for the SD in lane offset.

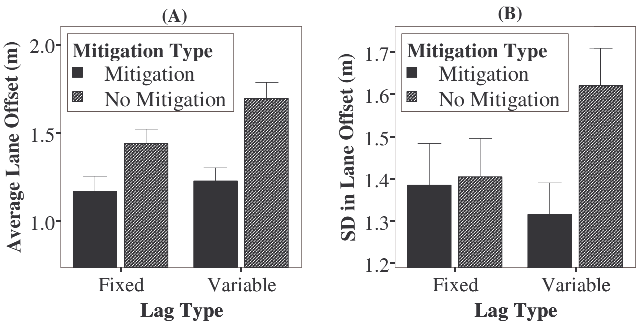

Figure 2. (A) Average lane offset and (B) SD in lane offset

Vehicle Speed

A mixed linear model revealed a mitigation type ($p < 0.01$, $F_{1,\ 112} = 65.3$) and order ($p < 0.01$, $F_{11,\ 112} = 5.4$) main effect for average velocity. Participants drove significantly faster with the mitigation than with no mitigation – Figure 3. Pairwise comparisons also revealed that participants drove significantly slower in the 1st driving trial than in 9 of the 11 subsequent trials ($p < 0.01$). The average speed on the 1st trial was 24.4 ± 2.3 mph, while the average speed on the 11 subsequent trials was 30.0 ± 0.5 mph. There was no lag type main effect for vehicle speed. A mixed linear model without the 1st trial revealed similar results: a mitigation type effect ($p < 0.01$, $F_{1,\ 102} = 82.9$) and no lag type main effect or mitigation-lag type interaction. The SD in velocity was also analyzed using a linear mixed model; however, there were no lag type, mitigation type, or order main effects.

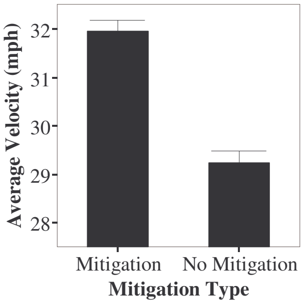

Figure 3. Average velocity

DISCUSSION

This experiment examined effects of both fixed and variable lag on a drive-by-wire/remote driving, as well as the ability of a predictive display to mitigate the effects of fixed and variable lag on driving performance. Participants were tasked with controlling a simulated vehicle along the right lane of simulated test course. This experiment demonstrated the ability of a variable lag to disrupt driving accuracy more than a fixed lag and also demonstrated the ability of a predictive display to mitigate the effects of lag on driving speed and accuracy.

Results from this experiment indicate that the presence of a variable lag in human-in-the-loop control systems may reduce lane following accuracy more than that of a fixed lag when no mitigation is present. When controlling the simulated vehicle, participants experienced greater lane offset (average offset and SD in offset) with the variable lag than with fixed lag. Degraded lane following accuracy under variable lag was most likely a result of the operator's inability to account for varying response to control inputs. Researchers have demonstrated human's ability to adapt to temporal visual discrepancies; however, these adaptations are generally associated with a fixed time delayed response to control inputs – for example, controlling simulated vehicle under a fixed lag at a fixed speed [3;15]. Adaptation to variable lag is plausible; however, it is dependent on the magnitude and frequency of the time lag. If the magnitude and/or frequency of the time lag is such that it impairs the operator's ability to account for the time lag, adaptation may not occur [4;16]. Inability to account for the lag often results in the move and wait approach instead of continuous control and is often associated with time lags of at least 1 s [17]. The participants' control inputs (throttle depressions) are evidence of a possible move and wait approach for the variable lag condition (700 ± 400 ms).

Results from this experiment demonstrate the effectiveness of predictive displays in mitigating the negative effects of lag on a teleoperation task. Just as in previous research associated with predictive displays [18], the predictive display used in this experiment resulted in greater speed and accuracy (i.e., lane following) on a simulated driving task. This was true regardless of whether the lag was fixed or variable. The mitigation increased vehicle speeds by about 9% (3 mph) and decreased lane offset by about 24% (~1.25 feet). Enhanced speed and lane following accuracy with the predictive display was likely a result of display ability to reduce the temporal displacement between control input and response, resulting in near real-time response to control inputs (~70 ms lag).

It is plausible that such a predictive display can be implemented into camera-based control systems. As long as the relative position of the vehicle and the lag characteristics of the drive-by-wire/remote control system can be estimated, it is possible to create a semi-transparent marker on the video feed that represents the relative position of the vehicle in the environment in real time. Both vehicle position and control system estimates are routinely obtained for robotic systems [6;19;20]. Topography information from the vehicle's sensor systems [e.g., Laser Detection and Ranging (LADAR)] combined with dynamic characteristics of the vehicle could be used to further enhance the fidelity of the semi-transparent overlay by simulating the dynamic interaction (e.g., roll, pitch, and yaw) of the overlay with the terrain. In addition to directly improving driving performance, such predictive displays may aid operators in developing an understanding of the characteristics of the control system (i.e., training). In such a case, the display itself may not be necessary once the operator reaches the desired level of proficiency. Future efforts should examine the benefits of predictive displays in training operators to adapt to lags in control systems.

While the predictive display was beneficial in the current study, future efforts should also to examine the utility of the displays under different constraints. For example, it is possible that the semi-transparent image used here may consume greater portions of the operator's visual field for short lags. In this case, a different type of predictive display may be more beneficial – e.g., a predictive display that displays the direction and placement of the vehicle with a small cursor(s) along the vehicle's path [11]. Of course, this may only be necessary if performance decrements associated with the lag are not adequately abated by human adaptation [3]. A second issue for predictive displays similar to the one used in this experiment, is that a predictive display may modulate the operator's attentional focus – e.g., shift the operator's attention to the environment surrounding the display. Eye-tracking data may be particularly useful in unraveling this issue.

CONCLUSION

This study provided insight into the effects of variable lag on controlling remote and drive-by-wire systems, as well as insight into the effectiveness of predictive display in mitigating the effects of both fixed and variable lag on driving performance. The mitigation used in this study significantly improved driving performance, suggesting that predictive displays of this type may be useful in overcoming the negative performance effects of both fixed and variable time lags.

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