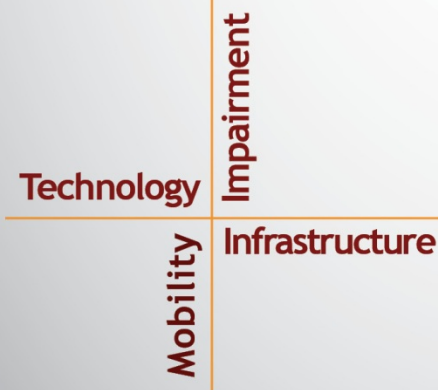# NSTSCE

National Surface Transportation Safety Center for Excellence

Strategies for Combating Drowsy Driving Using Adaptive Workload and Secondary Task Countermeasures

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Impairment

Technology | Mobility | Infrastructure

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EXECUTIVE SUMMARY

This study evaluated the effectiveness of alternative workload-based interventions intended to restore driver alertness following drowsy episodes. The study served as a proof of concept for varying the nature and onset of countermeasure interventions intended to disrupt the drowsiness cycle. Interventions to combat drowsiness attempted to target driver workload, either physical or cognitive, and included two primary treatment conditions: 1) physical workload to increase driver steering demands and 2) trivia-based interactive games to mentally challenge drivers. A benchmark comparison condition using music was also investigated to contrast the relative influence of workload-based interventions with passive listening to musical arrangements. The countermeasures considered were not intended to replace sufficient sleep, but rather to examine pragmatic interventions that may benefit drivers who are drowsy due to task underload.

The study also varied the onset stage of the intervention, basing either early or late onset on driver drowsiness levels indexed using a Percentage of Eyelid Closure (PERCLOS) measure. Unlike traditional drowsy driving studies, this experiment did not target sleep-deprived individuals, but rather studied normally rested drivers under the assumption that low-workload environments could trigger drowsy driving episodes. In other words, the study addressed drowsy driving cases resulting from boring conditions as opposed to those caused by lack of sleep or extended time-on-task-induced fatigue. Workload was used as the underlying mechanism to reengage drivers.

Thirty drivers, aged 21–70, completed a 3-hour trip in a driving simulator during which an experimenter at an external workstation monitored them for drowsy driving episodes. When a drowsy driving episode was identified, the driver received the prescribed countermeasure for a fixed 5-minute time period. The study method successfully induced multiple drowsy driving episodes of varying magnitudes and durations during the simulated trips. Drivers experienced an average of 8.81 drowsy driving episodes, with approximately 77% of the drivers experiencing five or more drowsy driving episodes during the 3-hour trip. Results suggest that both physical and cognitive workload-based countermeasures can effectively combat drowsiness and reengage drivers. Increasing the physical workload via steering demands and the cognitive workload via gaming interactions were equally effective at restoring drivers to an alert state following a drowsy episode, with average effectiveness levels of 98% and 87%, respectively. In contrast, listening to music was less effective, restoring drivers to an alert state about 68% of the time.

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LIST OF ABBREVIATIONS AND SYMBOLS

DMS	Driver Monitoring System
NDS	Naturalistic Driving Study
PERCLOS	Percentage of Eye-Lid Closure
SHRP 2	Second Strategic Highway Research Program
VTTI	Virginia Tech Transportation Institute

CHAPTER 1. INTRODUCTION

Drowsy driving has been estimated to be a significant causal factor in motor vehicle crashes, with estimates ranging from 6% to 21%, depending on the severity of the crash.[1] Recent estimates using data collected from the Second Strategic Highway Research Program Naturalistic Driving Study (SHRP 2 NDS) found the incidence of drowsy-driving-related crashes to be closer to 10%.[2] Although significant advances have been made relating to the detection and measurement of drowsiness and fatigue, the search for effective and practical countermeasures to combat drowsy driving has been elusive. One reason for this may be that research on drowsy driving has primarily focused on fatigue or sleep-deprived drivers as opposed to cases resulting from low workload or reduced driving task demands; remedies for the latter may not necessarily address the former. The work detailed here emphasizes low-workload situations that have been found to decrease a driver's general level of arousal, degrade driver performance, and induce drowsiness.[3,4]

This study evaluated alternative countermeasure strategies for proactively keeping drivers from entering into a drowsy state, or restoring driver alertness after the onset of drowsiness, by using workload-based countermeasures. The research provided opportunities to flag drowsy driving episodes over an extended 3-hour trip using a simulator with protocols designed to elicit drowsy driving epochs and examine the effects of various countermeasures. As suggested by Wierwille, "Drowsy drivers typically do not drop off instantaneously."[5] Rather, loss of alertness tends to be gradually preceded by measureable changes in performance or eye-state. The driver's state of alertness (i.e., drowsiness level), was indexed using Percentage of Eye-Lid Closure (PERCLOS) eye-state measures provided by a Driver Monitoring System (DMS); this measure has been found to be a reliable and sensitive indicator of drowsiness.[5] PERCLOS indexes the percentage of eye-lid closure, which is defined as the portion of time over a specific interval (typically a 1–3 minute period) where the eyes are 80% to 100% closed.

CHAPTER 2. METHODS

Researchers at the Virginia Tech Transportation Institute (VTTI) performed a simulator-based study using a RealTime Technology, Inc. simulator, a medium-fidelity, non-motion-based device specifically designed to assess human-machine interfaces in vehicles. The drive-on setup incorporated the use of a real vehicle—a 2006 Chevrolet Tahoe—positioned over a set of plates that allowed steering interactions to control the vehicle's placement and trajectory on the roadway scenes, which were presented on a large forward display screen. Brake and accelerator pedal controls were also active. The simulation setup was configured to collect PERCLOS measurements using a DMS installed on the Tahoe. The Tahoe was connected to the simulator, allowing extended drives with data from the DMS integrated into the simulation data stream. The study did not target sleep-deprived individuals, but rather evaluated normally rested individuals with seven or more hours of sleep (self-reported) under the assumption that low-workload environments could be used to elicit drowsy driving episodes.

COUNTERMEASURES

Although significant advances have been made in the detection and measurement of drowsiness and fatigue, the search for effective and practical countermeasures to combat drowsy driving has been relatively fruitless. It is hypothesized that efforts to develop interventions have been largely unsuccessful for two primary reasons. First, countermeasures may fail to intervene sufficiently early in the process to enable drivers to recover from drowsiness. Secondly, countermeasures may fail to address reduced workload, which is one of the underlying mechanisms responsible for inducing drowsiness in the first place. The countermeasure strategies explored as part of this effort were intended to address these limitations by adaptively managing and controlling drivers' workloads, increasing the demands early in the process when drivers first started to show signs of drowsiness. Combatting drowsiness was examined under the following three conditions:

1. Physical Workload: Drivers' physical workload was adaptively managed by varying the vehicle's steering and speed maintenance control inputs. Steering demand was manipulated by injecting artificial wind gusts, and cruise control usage was used to vary speed maintenance.
2. Game: Drivers' cognitive workload was adaptively managed using interactive trivia-based gaming.
3. Music: Drivers listened to music while driving as a comparison condition to the adaptive management conditions.

Research has shown that introducing artificial wind gusts in simulated environments can functionally increase steering demands, making it harder to maintain lane position and thereby increasing workload.[3] This same principle was used in the first intervention condition, Physical Workload, where drivers' workload was adaptively managed by using artificial wind gusts to increase steering demands and via cruise control. This altered the driving task demands in order to proactively keep drivers from entering into a drowsy state or to reengage them once they became drowsy. Researchers avoided creating extended periods of overly taxing or fatiguing situations, which could be counterproductive, by using short 5-minute bursts of high-workload periods to combat drowsiness. The second workload-based intervention condition, Game,

engaged drives in a trivia-based interactive game intended to increase cognitive workload. This activity was performed hands-free with the experimenter serving as the host and reading the questions and response options. Drivers received feedback after each question/response and were provided with their overall score. In the final condition, Music, some individuals experienced musical arrangements based on their musical preferences. Arrangements were automatically loaded by the experimenter and played through the vehicle's speakers. Before the driving session began, participants were asked to indicate their preferences among a library of songs. The use of music was meant to serve as comparison benchmark to assess the relative performance of the targeted treatments. The musical arrangements presented to drivers were randomly selected, and included musical styles drivers said they preferred as well as some they indicated disliking. The countermeasures explored as part of this research were not intended to address or replace the biological need to sleep, but rather to explore practical short-term interventions that may potentially benefit drivers who succumb to drowsiness as a result of task underload.

STUDY DESIGN

This study manipulated two basic parameters or independent variables: 1) countermeasure type, or treatment condition intended to combat drowsy driving episodes, and 2) onset stage of the countermeasure relative to the first flagged drowsy driving episode.

Countermeasure Type
(Two Levels, Between-subjects)

Countermeasure type consisted of a pair of interventions introduced to drivers to attempt to counteract or combat drowsiness by increasing workload either physically, by increasing steering demands, or cognitively, via an interactive trivia game. Each countermeasure condition included 10 drivers, remained active for a 5-minute period in order to control for exposure duration, and was administered following each drowsy episode. Countermeasures were repeatedly applied, as appropriate, each time drivers exhibited additional drowsy episodes.

Onset Stage
(Two Levels, Between-subjects)

Onset stage dictated when the countermeasure was injected relative to the driver's level or degree of drowsiness, and took advantage of work suggesting that drivers gradually succumb to drowsiness over time and do not instantaneously enter into a drowsy state. Early Stage onset introduced the countermeasures when reliable signs indicated the driver might have been getting drowsy based on measured PERCLOS threshold values (10% for Early Stage). The goal with Early Stage intervention was to act before drivers fell into a fully degraded state by introducing countermeasures at the first signs of impairment. In contrast, Late Stage interventions administered the countermeasures once drivers entered into a higher-level of drowsiness based on established PERCLOS threshold values (16% for Late Stage). Thus, within each countermeasure group, the sample was further divided into two onset conditions: Early Stage and Late Stage.

Participants

The research team recruited 30 drivers ranging in age from 21–70, with the average age being 43 years. The sample included 15 males and 15 females. Participants were paid $120 for participation in a single 3-hour session. All participants completed and signed an Informed Consent Form prior to their participation in the study. Participants were asked to follow to a prescriptive and systematic protocol in advance of the session in order to make them more susceptible to fatigue when driving, which included refraining from ingesting caffeinated beverages within 24 hours of the test session. Individuals were also asked to rate their current level of alertness at the start of the study session using the Karolinski Sleepiness Scale, with values ranging from "extremely alert" (value of 1) to "very sleepy, great effort to keep alert, fighting sleep" (value of 9). Drivers also self-reported their hours of sleep the night before the session. Participants were paid $120 for participation in a single four-hour session.

Simulator and Instrumentation

Participants were seated in a 2006 Chevrolet Tahoe connected to a medium-based fidelity, fixed (non-moving) simulator developed by RealTime Technologies, Inc. that was specifically designed to assess human-machine interfaces in vehicles (Figure 1). The drive-on setup incorporated positioning the Tahoe over a set of plates that allowed steering interactions to control the vehicle's placement and trajectory on the roadway scenes, which were presented in a large display screen at the front of the vehicle. Brake and accelerator pedal controls were also active. A single 3-hour driving scenario was used; this consisted of a freeway environment (two-lane divided highway) with no interchanges (on/off-ramps), overpasses, or traffic. These conditions were designed to mimic low-workload environments, resulting in a boring drive. The ambient lights in the simulator bay were turned off so that drivers were placed within a darkened environment with the intention being to help to induce drowsiness. Researchers instrumented the vehicle with a data acquisition system used to capture outputs from the DMS (e.g., driver gaze and PERCLOS).

Figure 1. Photographs. Simulator setup.

Procedure

Participants completed an Informed Consent Form, underwent simple vision and hearing screening tests, and completed a basic sleep questionnaire before commencing the study. Participants were informed that the purpose of the study was to understand driver fatigue and

vigilance over extended drives and how systems can be designed to combat drowsy driving. Individuals were informed that they would be taking a simulated 3-hour trip using a driving simulator, that there would be no rest breaks, and were then provided the opportunity to use the restroom facilities before proceeding to the vehicle. Participants were then escorted to the vehicle and simulator setup and shown the layout of the vehicle.

Individuals completed the 3-hour drive while the experimenter was seated at an external workstation monitoring for drowsy driving episodes. Individuals were assigned to one of the experimental sessions: either an early morning session from 7:00 a.m. to 11:00 a.m. or an afternoon session from 1:00 p.m. to 5:00 p.m. Drivers were asked to engage the cruise control at 60 mph during their drive, to do their best to track the center of the lane, and were reminded that their driving performance was being evaluated. Individuals were further instructed to remain in the right lane during the drive unless passing a slower moving lead vehicle; however, drivers never encountered a slower moving lead vehicle during the session. During the drive portion of the session, the experimenter injected the countermeasures as appropriate (countermeasures were treated as a between-subjects factor). Drivers in the Early Stage condition received a countermeasure when their PERCLOS levels reached 11%. Individuals in the Late Stage condition received countermeasures when their PERCLOS levels were at 16%. Drivers received the prescribed countermeasure for a fixed 5-minute time period, after which the intervention was terminated. Countermeasures were reinjected when PERCLOS threshold levels were reached again. In both Early and Late Stage conditions, the time intervals between successive drowsy driving episodes were used to evaluate the countermeasures' effectiveness. This measure essentially captures the potency of the intervention by examining the time intervals between drowsy driving episodes, allowing the lasting effects of the intervention to be examined. The presumption is that effective countermeasures will produce lasting effects leading to longer time intervals between drowsy episodes, while less-effective interventions will have relatively short intervals between episodes. Once the drive was completed, individuals were escorted back to the screening room where they completed a post-drive questionnaire and were compensated $120 for their participation.

CHAPTER 3. RESULTS

This section presents results associated with the countermeasure groups, examining each key dependent measure, including effectiveness, time to reach alert state, relative increase in PERCLOS, and mean intervals between drowsy episodes.

COUNTERMEASURE EFFECTIVENESS

The countermeasure effectiveness variable measures an intervention's effectiveness by assessing its ability to bring drivers back to an alert state following a drowsy episode. It is expressed in terms of the percentage of drowsy cases experienced by each driver wherein the countermeasure successfully returned them to an alert state within 5 minutes of introduction. Drivers were considered alert when PERCLOS dropped to 5% or less within 5 minutes of the countermeasure's introduction. For example, if a driver experienced eight drowsy driving episodes during the 3-hour trip, with countermeasures injected following each episode, and successfully responded to the intervention in four of these cases (PERCLOS below 5%), this would represent a 50% effectiveness level. Mean effectiveness levels across each countermeasure condition are illustrated in Figure 2, revealing significant differences among the treatment conditions, $F(4, 42) = 6.28$, $p < 0.0006$]. No significant differences were observed between Physical Workload and Game; however, Physical Workload was significantly more effective than Music.
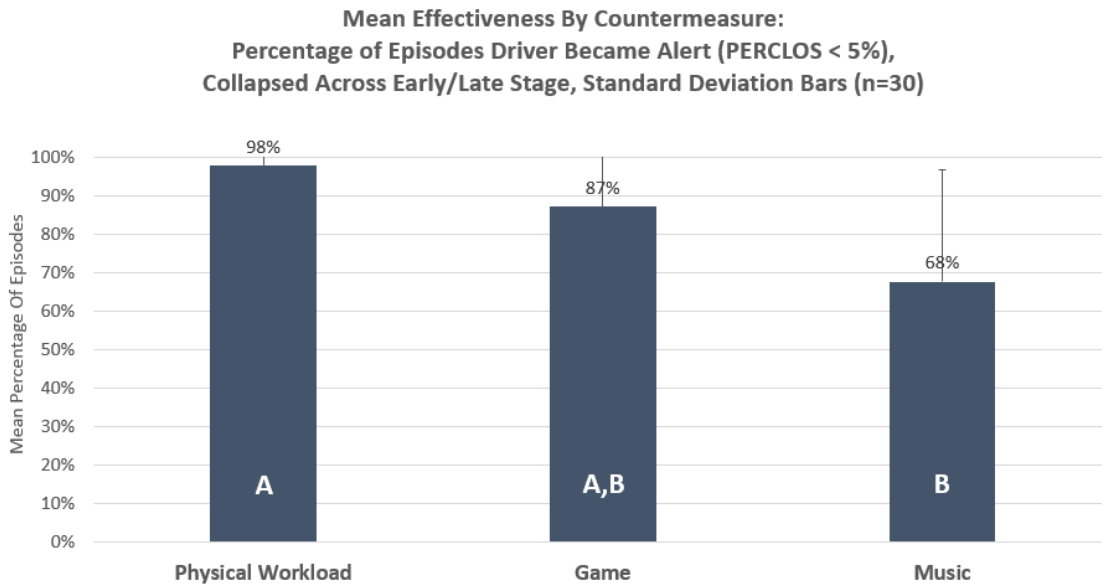

Figure 2. Graph. Countermeasure effectiveness: percentage of drowsy driving epochs where the intervention successfully brought drivers back to an alert state.

TIME TO ALERT STATE

The time to alert state variable, measured in minutes, represents the time needed to bring drivers back into an alert state following a drowsy episode. It is operationally defined as the interval from the onset of the intervention's injection to the point where PERCLOS dropped to under 5%.

Figure 3 illustrates the mean alert state times across the interventions, revealing significant differences among these treatments, $F(4, 42) = 7.93$, $p < 0.0001$. Similar to the earlier results, data suggest that Physical Workload and Game were equally effective in terms of the average time needed to reengage drivers. Physical Workload reengagement time was also significantly faster than reengagement time for Music.
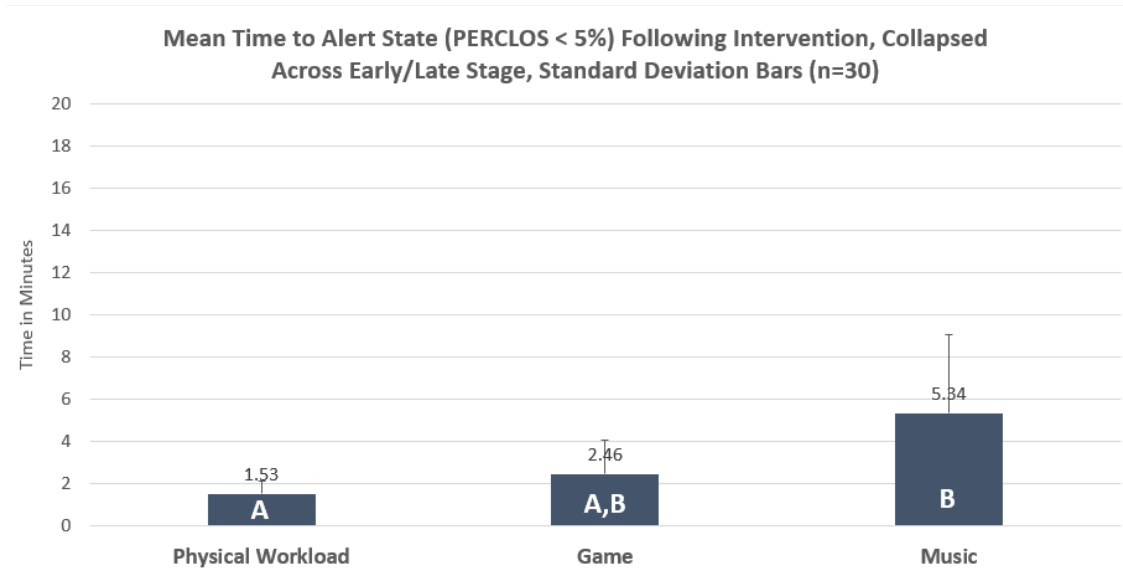

Figure 3. Graph. Mean time to alert state following introduction of the countermeasure.

INCREASE IN PERCLOS

The increase in PERCLOS indicates the average peak increase in PERCLOS beyond the threshold levels following countermeasure injection. Increasing PERCLOS levels may indicate that a countermeasure is not working or is slow to act. Lower peak increases represent greater countermeasure effectiveness. Figure 4 presents the mean relative increase in PERCLOS across the interventions, revealing significant differences among these conditions, $F(4, 42) = 4.79$, $p < 0.003$. Specifically, results found that Physical Workload and Game were equally effective in terms of arresting additional PERCLOS increases, and that these interventions were significantly better than Music.
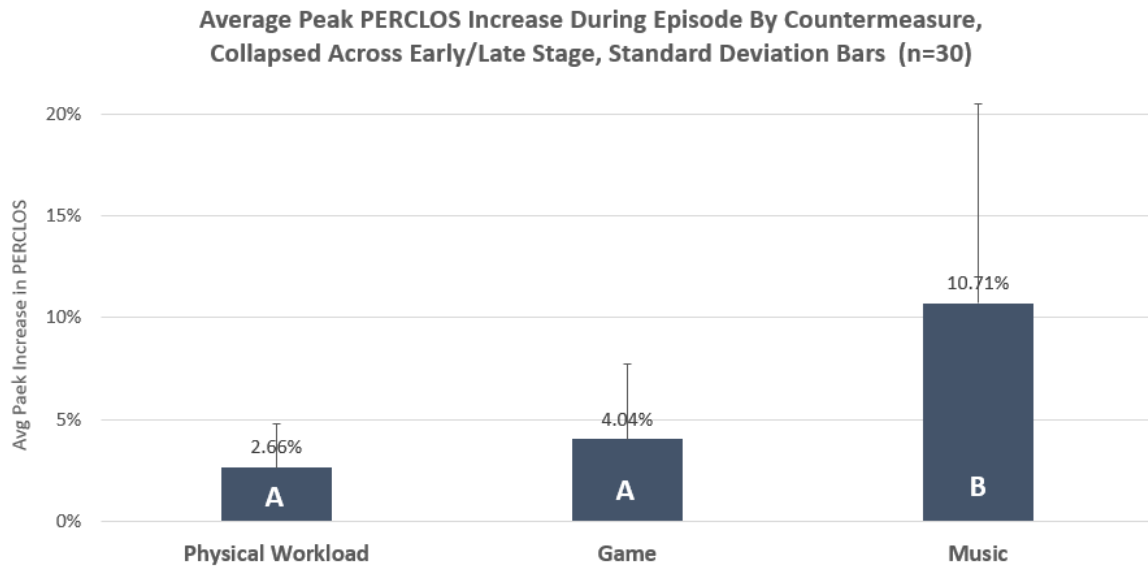

Figure 4. Graph. Average peak PERCLOS increase following introduction of the countermeasure.

INTERVAL BETWEEN DROWSY EPISODES

The interval between drowsy episodes measure essentially captures the potency of the intervention by examining the time intervals between drowsy driving episodes, allowing the lasting effects of the intervention to be examined. The presumption is that effective countermeasures would produce lasting effects leading to longer time intervals between drowsy episodes, while less effective interventions would have relatively short intervals between episodes. Figure 5 plots the mean time intervals between drowsy episodes across each of the interventions, with time intervals averaging between 19.22 and 31.82 minutes. In this case, the overall analysis of variance was not significant, $F(4, 40) = 1.06$, $p < 0.39$, indicating that, on average, time intervals across these three conditions were not significantly different. Nevertheless, it should be noted that there was a trend for individuals who received the Game intervention to have longer durations between drowsy episodes (averaging 31.42 minutes) compared to those in the Music group, who averaged 19.22 minutes, representing a 63% increase.
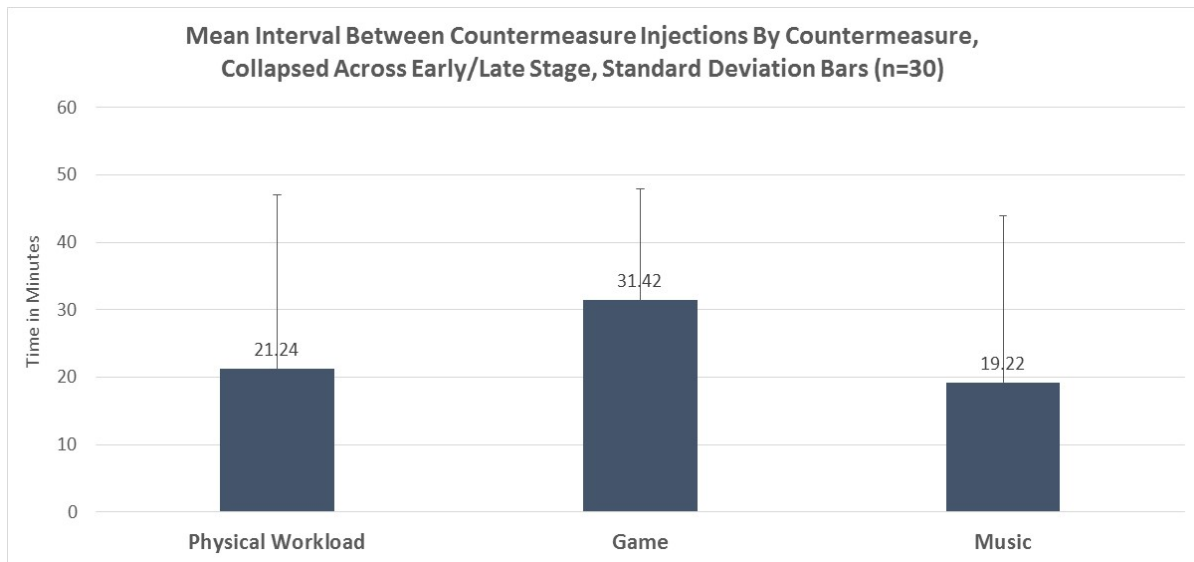

Figure 5. Graph. Mean interval between countermeasure injections.

EARLY VERSUS LATE STAGE

One factor examined as part of this research was countermeasure onset stage, with interventions introduced either at the first sign of drowsiness (Early Stage) or after drivers entered into a more advanced level of drowsiness (Late Stage). Both stages were defined based on the driver's PERCLOS levels, with Early Stage onset occurring when PERCLOS reached 10% and Late Stage onset occurring when PERCLOS levels exceeded 15%. Contrasts between Early and Late Stage onset were used to examine each countermeasure's ability to revive drivers at different levels of drowsiness.

Results found that, in general, countermeasures were equally effective under both Early and Late Stage conditions, and were not significantly influenced by type of intervention; neither the main effect of Stage nor the interaction effect between Countermeasure and Stage were significant. As

shown in Figure 6, differences between Early and Late Stage conditions yielded comparable outcomes with the exception of one measure: the mean interval between drowsy episodes, $F(4, 37) = 11.20$, $p < 0.002$. Specifically, when collapsed across all countermeasures, inter-episode intervals lasted an average of 36.24 minutes under the Late Stage condition, and an average of 13.51 minutes under the Early Stage condition. Differences may largely be due to the simple fact that Late Stage triggers only occurred when PERCLOS values exceeded 15%, which means that they took longer to occur than Early Stage triggers; Late Stage events were indeed fewer in number (average of 7.26) than comparable Early Stage events (average of 10.04).
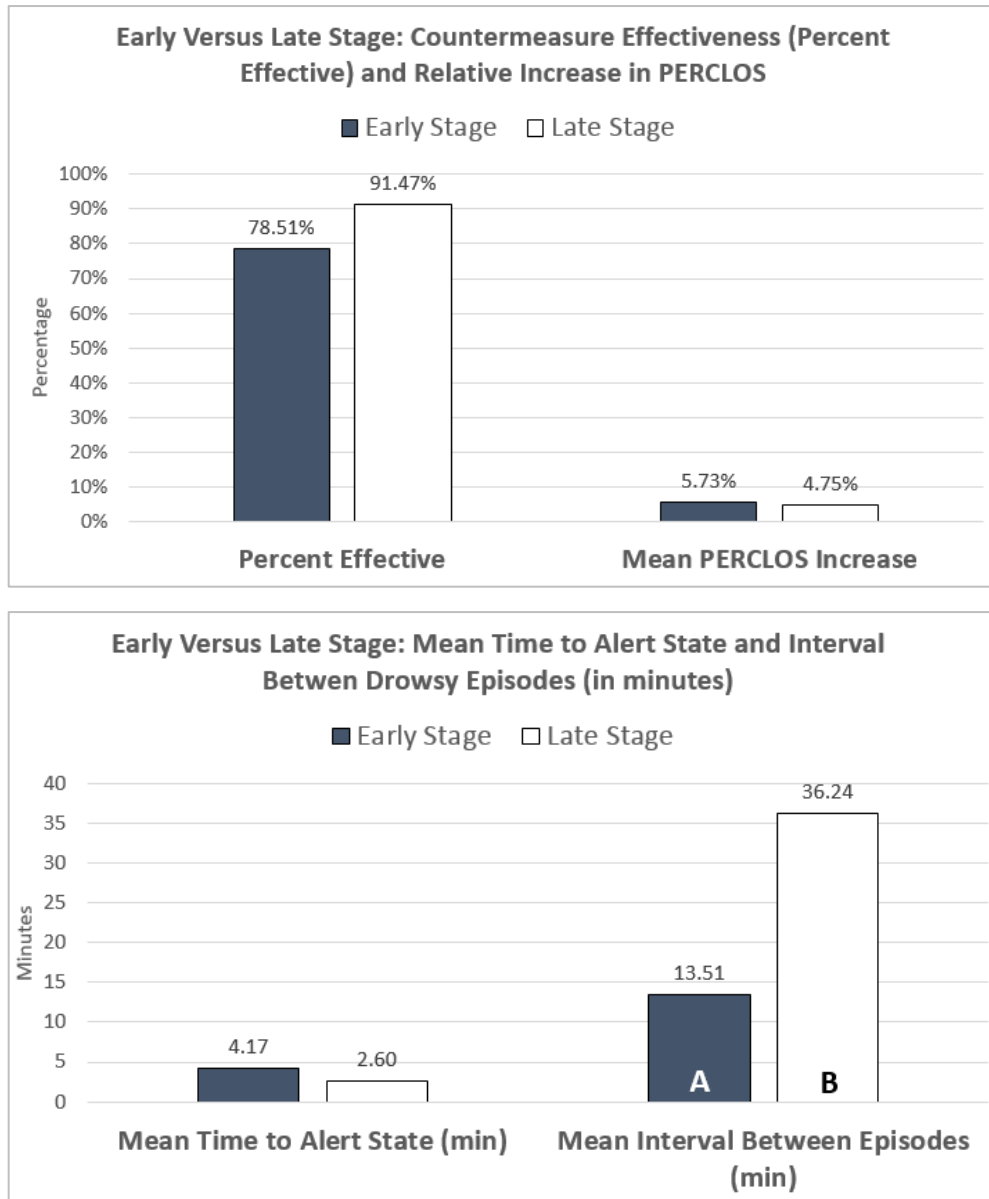

Figure 6. Charts. Effects of Early- and Late-Stage manipulations. Impact on countermeasure effectiveness and PERCLOS increase (top chart), and time to alert state and interval between drowsy episodes (bottom chart).

EFFECTS OVER TIME

This section presents data related to countermeasure effectiveness over time, addressing the extent to which drivers acclimate to an intervention following repeated exposures, potentially reducing its potency or effectiveness. Figure 7 depicts the effectiveness timeline detailing the mean time to recover to an alert state following the countermeasure's introduction during each drowsy episode. As illustrated, drivers appear to habituate to the Music intervention, showing progressively longer recovery times with subsequent drowsy episodes. For example, time to recover following the first drowsy episode averaged 3.49 minutes, increased to 5.95 minutes following the second episode, and reached 7.59 minutes after the third episode. Although performance appeared to rebound during the fourth episode (possibly as a result of introducing novel music, though this is speculative), recovery times continued to climb during the fifth and sixth episodes. This general trend suggest that music's effectiveness may decline over repeated exposures. In contrast, Physical Workload interventions were relatively stable over time.
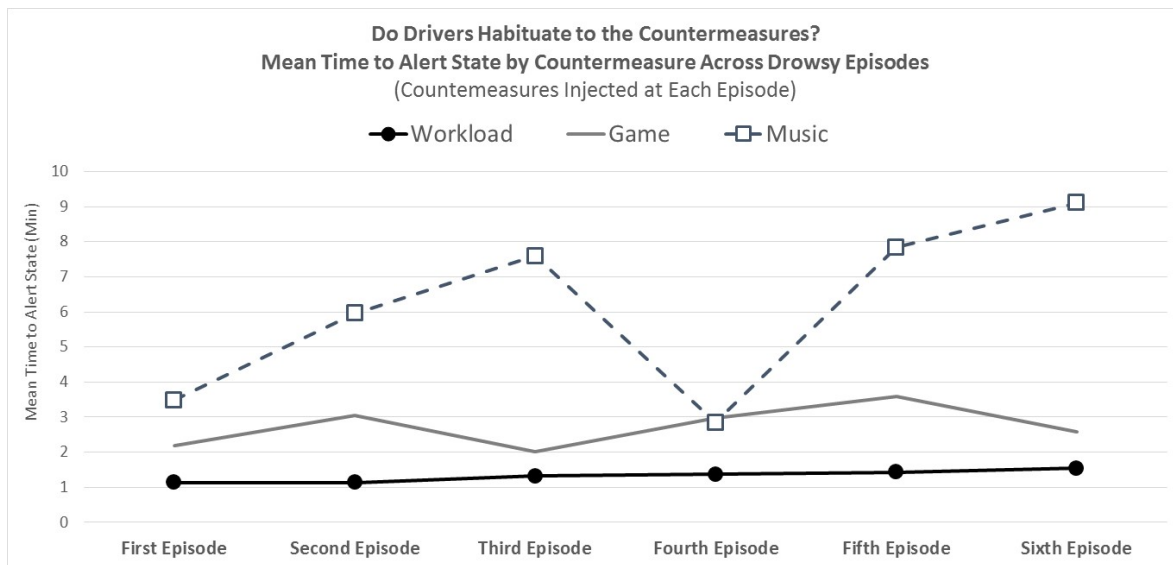

Figure 7. Graph. Time to alert state as a function of countermeasure and drowsy episode.

CHAPTER 4. SUMMARY AND CONCLUSIONS

This study explored strategies for restoring driver alertness following drowsy driving episodes. A key hypothesis was that reduced workload is a significant underlying mechanism responsible for inducing drowsiness in otherwise normally rested individuals. Unlike some drowsy driving studies, this experiment did not target sleep-deprived individuals, but instead recruited normally rested drivers under the assumption that low-workload environments could be used to occasion drowsy driving episodes. Moreover, interventions to combat drowsiness attempted to target physical or cognitive driver workload and included two primary treatment conditions: 1) Physical Workload, during which driver steering demands were increased, and 2) Game, which used trivia-based interactive games to cognitively challenge drivers. A third condition, Music, used music listening to assess the relative influence of workload-based interventions by contrasting workload-based interventions to listening to music.

Thirty participants, ages 21–70, completed a 3-hour simulated drive using a medium-based fidelity, fixed-base (non-moving) simulator. PERCLOS was utilized to measure driver alertness, as it is one of the more robust and well documented indices of driver alertness. PERCLOS indexes the percentage of eye-lid closure defined as the portion of time over a defined interval (typically over a 1–3 minute period) where the eyes are 80%–100 % closed. The driving scenario was designed to mimic low-workload environments with no interchanges (on/off-ramps), overpasses, scenery, or traffic conditions, resulting in a boring drive. The experimenter was seated at an external workstation to monitor for drowsy driving episodes and injected countermeasures as appropriate. Some participants received a countermeasure at the first signs of impairment, or the Early Stage, when their PERCLOS levels exceeded 10%, while others received countermeasures once they were well into a drowsy condition, or at the Late Stage, when their PERCLOS levels were at 16%. Drivers received the prescribed countermeasure for a fixed 5-minute time period after which the intervention was terminated.

Results suggest that both physical and cognitive workload-based countermeasures were effective at combating drowsiness under these test conditions. Increasing physical demands and engaging drivers in a trivia-based game were equally effective at restoring drivers to an alert state following a drowsy episode, with average effectiveness levels of 98% and 87%, respectively. Effects lasted an average of 21 minutes for physical workload interventions and over 32 minutes for cognitive workload interventions. In contrast, listening to music was only partially effective, restoring drivers to an alert state about 68% of the time, with effects averaging approximately 20 minutes. Data also suggest that drivers are not likely to habituate to changes in physical workload or cognitive interactions; these treatments do not appear to lose potency with repeated exposures as indexed by the time needed to bring drivers back to an alert state. However, music's effects appear to progressively decrease with repeated exposure under the conditions examined. Recent published studies reinforce the basic concept that drowsy driving can result from low workload and that use of trivia-based games can serve as an effective countermeasure since it increases cognitive workload.[4,6]

Physical Workload (increasing steering demands)

- Effective 98% of the time, bringing drivers back to an alert state (PERCLOS < 5%) within an average of 1.53 minutes.

- Average peak PERCLOS of 15.43%. Peak PERCLOS levels increased by an average of 2.66% following its introduction.
- Effects lasted an average of 21 minutes.

Game (interactive trivia-based game)

- Effective 87% of the time, bringing drivers back to an alert state (PERCLOS < 5%) within an average of 2.46 minutes.
- Minimized peak PERCLOS levels, increasing by an average of 4.04% following its introduction. Average peak PERCLOS of 17.37%.
- Longest lasting effects at an average of over 32 minutes.

Music (listening to a selection of music)

- Effective 68% of the time, bringing drivers back to an alert state (PERCLOS < 5%) within an average of 5.34 minutes.
- Average peak PERCLOS of 25.43%. Peak PERCLOS levels increased by an average of 10.71% following its introduction. Results suggest drivers continued to grow progressively drowsier even during the music intervention.
- Effects lasted an average of 20 minutes.

This study served as a proof of concept varying the nature and onset of countermeasure interventions intended to disrupt the drowsiness cycle. Countermeasures explored as part of this research were not intended to address or replace the biological need for sleep, but rather explore practical, short-term interventions that may potentially benefit drivers. The work in this study targeted drowsiness resulting from driver underload—low-workload conditions—as opposed to lack of sleep or fatigue due to extended time on task.

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