

*Audio Cueing and Negative Adaptation in Older and Younger
Drivers Using Lane Departure Warning Systems*

by

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*A thesis submitted in conformity with the requirements
for the degree of Master of Science*

**Institute of Medical Science
University of Toronto**

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2015

Abstract

A Lane Departure Warning System (LDWS) is an automation system that can be integrated in vehicles. Empirical research has demonstrated conflicting results about the effectiveness of LDWS, which may be attributable to inconsistent warning cues, adaptation effects, and differences among user populations. In this thesis, I investigated whether meaningful or non-meaningful auditory cues are more effective in improving lane keeping in older and younger drivers, and if adaptation occurs with the use of either/both cue types when the LDWS was intermittently turned off. Results showed LDWS were initially helpful in reducing lane deviations, regardless of cue type, with non-meaningful cues showing slightly greater effectiveness, particularly in older adults. However, following exposure to LDWS, drivers exhibited short-term negative adaptation to the system, displaying significantly more and larger lane deviations when the system was on compared to when it was off. Significant adaptation differences between younger and older adults were not observed.

Acknowledgments

Over the past two years, I have had the incredible opportunity to work with and have support from a number of amazing individuals. Without their guidance, the completion of this thesis would not have been possible.

To Dr. Andrea Furlan: thank you for supporting me throughout this journey and believing in me, even when the tasks at hand seemed insurmountable. Your guidance has helped me develop technical research skills and your kindness has helped make this thesis an incredible learning experience. It was a privilege to work with you.

To Dr. Jennifer Campos: your mentorship throughout this thesis has been invaluable. Thank you for standing by me every step of the way, offering wisdom and guidance throughout the critical times. Your enthusiasm and dedication is inspiring and I have learned so much from working with you over the past two years. Words cannot express my appreciation for everything that you have done. I am truly honoured to have had the opportunity to work with you.

To Dr. Bruce Haycock: I could not have done this without you. Thank you for taking the time and effort to help me with all of the challenging technical aspects of this project and your endless support. Your patience and willingness to teach allowed me to learn skills far outside what I had ever expected, and your moral support helped ease long days of data collection and analysis. I am incredibly lucky to have had such a dedicated and skilled mentor.

To Dr. Geoff Fernie: thank you for your insightful inquiries and suggestions stressing thoroughness throughout the research process. Your expertise and feedback has helped shaped this project and always reminded me to consider both the details and the big picture aspects of a research problem.

Additional thanks to Dr. Linda Boyle, Dr. Robert Mann, and Dr. Birsan Donmez for their time and willingness to act on my defense committee as the external appraiser, examiner, and internal appraiser, respectively.

To my colleagues on the TRI Technology Team: at some point or another each of you played a significant role in the completion of this work- whether it was stopping by my desk to offer words of encouragement, taking time to sit with me and walk through coding, offering time to come in early or stay late on data collection days, or offering up chocolate to cheer up late nights at the lab. Not only have you shared a wealth of knowledge and experience with me, you have filled these past two years wonderful laughs and unforgettable memories.

To my friends and family: I am eternally grateful for your love and support throughout this endeavour. From listening to me endlessly talk about the “outrageously cool motion simulator” I had the opportunity to work with, to supporting long hours of work with free meals and loving phone calls, you made this possible. Specifically to my mother, father, and sister, thank you for being the most supportive family anyone could ever imagine.

Contributions

The work presented in the following thesis was conducted in the iDAPT Challenging Environment Assessment Laboratory at the Toronto Rehabilitation Institute, 550 University Ave. site. The project was approved under the University Health Network Research Ethics Board (REB #14-7769).

I was the primary investigator of this project, responsible for all major areas of formation of the project concept, obtainment of research ethics approval, design of driving courses in OKTAL's SCANeRTM studio, participant screening, data collection, data analysis, and manuscript composition.

Dr. Andrea Furlan was the supervisory Principle Investigator of this project, involved with formation of the study concept, project oversight, and manuscript editing.

Dr. Jennifer Campos was involved throughout the project in formation of the study concept, supervisory of data collection, methodology development, and manuscript editing.

Dr. Bruce Haycock was involved in the early stages of the project design, design of driving courses in OKTAL's SCANeRTM studio, integration of software with the CEAL 6-axis motion simulator, coding of the MATLAB script used for data analysis, and partial manuscript editing.

Susan Gorski and Larry Crichlow were responsible for running the motion base simulator throughout data collection while participants and myself completed the experiment inside the simulator.

Robert Ramkhalawansingh was involved in partial design of data analysis methods.

Funding for this project was provided through the DriverLab research fund at Toronto Rehabilitation Institute.

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List of Abbreviations

ADAS: Advanced Driver Assistance System

LDWS: Lane Departure Warning System

LoA: Level of Automation

HMI: Human-Machine Interaction

LKS: Lane Keeping System

ISO: International Standardisation Organization

IIHS: Insurance Institute for Highway Safety

TRI: Toronto Rehabilitation Institute

iDAPT: intelligent Design for Adaptation, Participation and Technology

MSSQ-S: Motion Sickness Susceptibility Questionnaire (Short)

MoCA: Montreal Cognitive Assessment

CEAL: Challenging Environment Assessment Lab

FMS: Fast Motion Sickness Scale

SSQ: Simulator Sickness Questionnaire (Short)

SS: Simulator Sickness

nDev: Number of Deviations

TimeDev: Time of Deviations

MagDev: Magnitude of Deviations

VelX: Velocity in the forward direction

Chapter 1

Overview

Across the globe, driving-related injuries are the eighth leading cause of death (WHO, 2013). Each year, over one million people die in road-traffic incidents (WHO, 2013). In Canada alone, driving-related injuries and fatalities cost the health care system approximately 10 billion dollars annually; the equivalent to about 1% of the country's GDP (Transport Canada, 2011). In an effort to reduce these statistics, provide drivers with more information and comfort, and enhance traffic flow, advanced driver assistance systems (ADAS) have been introduced as a primary focus of modern day vehicle design. ADAS are designed to aid and assist the vehicle operator with driving tasks through various means. Their level of assistance ranges from providing basic informational cues, to warnings of possible danger, warnings and guidance throughout the dangerous situation, or a full override of the driver with the vehicle independently taking action (Reimer, 2014). As advances in in-vehicle technologies are made, manufacturers are eager to produce products with the newest, most innovative features. Supporting research, however, has not been able to keep pace with the fast growing demand for ADAS. While ADAS are designed to theoretically increase safety of driving, the practical safety implications are not yet well understood.

Lane departure warning systems (LDWS) were originally developed to assist commercial trucks with lateral control, LDWS issue a warning to the driver when the vehicle is crossing, or is on a trajectory to cross, an adjacent lane boundary (Cualain, Hughes, Glavin, & Jones,

2012). Empirical evidence has shown conflicting results regarding the effectiveness of these systems with some sources showing beneficial effects on lane keeping performance (e.g. Navarro, Mars, & Hoc, 2007; Rossmeier, Grabsch, & Rimini-Doering, 2005), while others report more negative driving outcomes, such as unintended adaptation effects (e.g. Rudin-Brown & Ian Noy, 2002). Despite the fact that most major vehicle manufacturers have now integrated LDWS into certain vehicle models, there are marked differences among the warning cues selected. With options for audio, visual, and haptic warnings, a review of current vehicle models reveals audio cueing is a commonly selected warning type for LDWS. Importantly, there is a considerable gap in knowledge regarding which features of auditory LDWS are most effective and whether adaptation to these cueing systems can optimize their effectiveness. Moreover, there is significant lack of understanding in how the use of audio cue based LDWS may affect different driver populations, specifically, there is reason to suspect that older drivers may respond differently to these systems.

In the introductory chapters of this thesis, I will review the literature and describe the rise of vehicle automation, the use of ADAS to support improved driving performance, and the potential concerns with their implementation. Gaps within the field will be identified and concentrated to formulate the primary research objectives and hypotheses of this thesis (Chapter 4). The design methodology for this experiment will be presented and results will be discussed in terms of filling in some of the research gaps outlined throughout the literature review (Chapter 5). To conclude, I will present overall findings and limitations for this work and discuss future directions for building upon this research (Chapter 6).

1.1 Vehicle Automation

In recent years, there has been exponential growth in technology advancements for personal motor vehicle design. With this growth, ADAS have become a major focus of modern day vehicles (Jamson, Merat, Carsten, & Lai, 2011). Designed to increase driving safety and efficiency, these systems can assist in identifying, mitigating, and alerting drivers of potential risks. Systems such as front collision warning systems, back-up cameras, adaptive cruise control, blind spot detection, lateral control aids, and parking aids are just a few examples of available ADAS (Campbell, Richard, Brown, & McCallum, 2007). With the potential to dramatically change the driving experience (positively or negatively), ADAS must be carefully designed, evaluated, and implemented.

The following chapter will explore the development of automated technology for vehicles, technical aspects of one particular type of ADAS, that is LDWS, and the recent discussion surrounding their use.

1.1.1 Human-Machine Interaction

Ushered in by the technological revolution, the evolution of automation has proliferated in a variety of sectors ranging from household items to complex vehicle control. Parasuraman and Riley suggest a definition for automation in its most simplistic format as the “execution by a machine agent of a function that was previously carried out by a human.” (Parasuraman & Riley, 1997, pg.231) In a contemporary driving context, automation refers to the acquisition of external variables, processing, and output of direct control or informational cues to a vehicle’s operator.

The benefits and detriments of automation across technology sectors has been an area of extensive investigation over the past twenty years. At the forefront of this discussion is the concept of level of automation (LoA), which signifies the degree to which a technology takes on the role of the operator's workload (Endsley & Kaber, 1999). While several scales of LoA have been presented in the literature (Flemisch et al., 2008; Kaber & Endsley, 2004; Sheridan, 1992; Wei, Macwan, & Wieringa, 1998), there is consistency among these scales with respect to the extremes of the spectrum; LoA can range from fully manual (human operated) to fully autonomous (machine operated). In the realm of driving, five automation levels have been outlined: (0) No automation: driver holds complete control of all driving functions, (1) Function-specific automation: automation system is used to control one or more specific functions, (2) Combined-function automation: multiple automation systems are used in combination for control over specific functions and driver holds intervention capability, (3) Limited self-driving automation: automation systems take on almost total functionality, but occasional driver intervention is possible, (4) Full self-driving automation: automation holds complete control of all driving functions (National Highway Traffic Safety Administration, 2013). In general, high-level automation is widely accepted in relatively mundane, low-risk situations, where technology is better suited to provide efficiency and precision over a human operator (Parasuraman, Sheridan, & Wickens, 2000). For example, robotic assembly lines found in food production factories run fluidly, producing high quality results at rates far faster than human assembly tactics. In contrast, universal acceptance of high-level automation is much lower for complex, safety-critical tasks and unpredictable environments (Abbink, Mulder, & Boer, 2012). These tasks may rely on human cognitive processing to evaluate risk and develop appropriate

responses. For example, in the medical domain, health care practitioners are required to physically evaluate and interpret findings to diagnose and treat patients. In this scenario, the human ability to dynamically assess, process, and problem solve lends itself more appropriately to the task than a machine. Noting the extreme ends of the LoA spectrum, the majority of automation lies in the mid-range, giving the rise to the term semi-automation.

Semi-automation encompasses automation that keeps a human operator in the loop with some level of control. The relationship of shared control, known as human-machine interaction (HMI), is both complex and variable. In terms of driving, many ADAS are semi-automated technologies that rely on both machine and driver to work cooperatively in order to operate effectively. The complication in this is that the responsibilities and roles of each party become convoluted. Therefore, it is crucial that the HMI is carefully considered during the technology's design process (Sheridan & Parasuraman, 2002). In 1990, Norman noted the criticality for a human operator and automated system to intuitively understand each other's roles through continuous, active feedback in order to operate cooperatively (Norman, 1990). This concept was further developed to include the notion that an autonomous system should use human input to ensure the system is functioning as anticipated and there is opportunity for manual override in critical situations or unexpected circumstances (Billings, 1997; Hoc & Blosseville, 2003; reviewed in Kaber & Endsley, 2004; Sheridan, 1992). When designing ADAS, there should be substantial focus on optimizing the HMI with these considerations for feedback, control and override options. Otherwise, there is risk of inappropriate integration with the driver's sensorimotor control loop, which may result in unexpected changes to driving performance (Hoc

& Blossville, 2003). Identifying the optimal HMI in ADAS is challenging, as each system type plays a different role in the driving task and drivers are inherently unique in how they use the technology. Dedicated research for each ADAS is required to fully understand how these systems can best be integrated and used by drivers of all ages and abilities. This thesis will explore one commonly integrated ADAS: LDWS.

1.1.2 Lane Departure Warning and Lane Keeping Systems

Single-vehicle road departure crashes have been identified as the leading fatality crash type among all road accidents (Barickman, Smith, & Jones, 2007). It has been reported that this crash type accounts for approximated 21% of all reported vehicle crashes and 37.4% of all fatal crashes (Wang, 1994). In effort to mitigate road-departure crashes, the concept of lateral control assistance technology was introduced. Studies have suggested that LDWS may have the potential to prevent approximately 10% of road departure crashes, thereby reducing the number of injuries and fatalities associated with the crash type (Pomerleau et al., 1999). Seeing the immense potential of lateral control assistance technologies, vehicle manufacturers and researchers alike have invested in the development and patenting of various types of systems.

Lateral control assistance technologies exist in two formats: LDWS and lane keeping systems (LKS). LDWS warn the driver via a visual, auditory, and/or vibrotactile cue when the vehicle exits its current lane. The warning is disabled when the vehicle resumes a position fully within its lane or when the driver, prior to changing position, activates the right or left turn signal. LKS use the same warning tactics as LDWS, however, LKS will automatically correct the steering

wheel angle if the vehicle begins to exit its current lane and action is not taken by the driver to correct the position when the warning has triggered. For the purposes of this work, we will focus our attention to LDWS- the most commonly integrated of the two system types.

LDWS rely on input from sensors which track vehicle position relative to the lanes. Typical sensor types include camera sensors (charge coupled device or complementary metal oxide silicone) mounted behind the windshield, laser, radar, or infrared sensors mounted under the vehicle (Cualain et al., 2012). Camera sensors provide the added benefit of prompting warnings prior to making contact with the lane boundaries, but are limited by environmental factors that may obstruct lane marking visibility (e.g. snow covered roads) (Cualain et al., 2012). Infrared sensors rely on the detection of reflected beams emitted by the system's diode. Unlike camera systems, infrared sensors are unaffected by poor lane visibility, however, they can only detect and issue a warning cue once the vehicle has made contact with the lane boundary (Cualain et al., 2012). Roadway markings are a critical component to LDWS functionality and can be affected by visibility, sensor quality, road conditions (snow, salt, water etc.), marking type, and lighting conditions. While a 100% reliable system is ideal, with current models there is a trade-off; is it better to have high reliability under most conditions and low reliability in a few conditions, or moderate reliability across all conditions? (Visvikis, Smith, Pitcher, & Smith, 2008) It is under these conditions of fragmented reliability that the notion of behavioural adaptation may be of most concern (See section 1.3). Further research into sensor design, lateral position algorithms, and lasting impact on driving behaviour is required to address these types of questions.

To date, there is no formal regulation governing the minimum requirements for LDWS. The International Organisation for Standardization (ISO), a non-governmental body affiliated with 164 countries, has developed a set of voluntary guidelines to advise on the development and use of LDWS in personal motor vehicles. ISO 17361:2007 outlines warning thresholds, speed thresholds and road curvature thresholds for LDWS use and notes environmental factors and system reliability as common concerns (ISO, 2007). While these guidelines are helpful for LDWS technical design, standardization for the human-machine interface, or a clear understanding of how the warnings are best presented to the driver, have been neglected. It is only now, after LDWS have been integrated, that conversation regarding the effectiveness of different types of warning signals and how this may be related to particular driver populations has been sparked.

In these systems, warning alarms are communicated to the vehicle operator through one or more sensory stimuli. Visual cues to symbolize warnings are often projected on the dashboard panel in the form of coloured icons. Audio cues to alert a driver to danger are found in directional formats (sounding from the side of the car where danger is detected) and global formats (sounding uniformly within the car when danger is detected). Vibrotactile cues to warn drivers of potential danger can be located in various locations such as the seat or steering wheel, and similar to audio cues, can transmit directional or global warnings. The integration, format, and location of these sensory stimuli are unique to vehicle makes and models.

1.1.3 Recent Controversy

Three types of crashes typically associated with LDWS are: 1) a vehicle leaving its lane and colliding with oncoming traffic in the opposite lane, 2) a vehicle leaving its lane and colliding with adjacent traffic travelling in the same direction, and 3) a vehicle leaving its lane and colliding with a stationary object off the road (LeBlanc et al., 2006). From a theoretical perspective, LDWS is a promising solution to assist in the prevention of each of these crash types by alerting drivers to unintentional lateral drifting. In reality, there has been recent questioning as to if LDWS actually prevent crashes or if they may play an unintentional role in perpetuating them under certain conditions. For instance, through recent data obtained by the Highway Data Loss Institute, the Insurance Institute for Highway Safety (IIHS) has released alarming statistics showing that LDWS may, in fact, be doing more harm than good (IIHS, 2012). The IIHS examined data from three vehicle makes (Mercedes-Benz, Buick and Volvo) with integrated LDWS systems. Both Mercedes-Benz and Buick vehicles showed significant increases (5% and 4% respectively) in the number of accidents with which they were involved. Moreover, both makes displayed higher rates (greater than 10% increase in Mercedes) of property damage claims compared to vehicles without LDWS. While Volvos showed positive performance (decreased crashes and damage claims), the IIHS suggests this may be due to the LDWS pairing with forward collision warning and automatic braking. The values presented in this report suggest serious and valid concerns with the implementation of LDWS. Importantly, the causes of these higher crash rates and damage claims associated with LDWS are unknown and therefore, carefully controlled empirical studies are required.

In reviewing the technical characteristics of LDWS, inconsistencies become apparent. The majority of LDWS systems use auditory cueing as the warning method for lane departure, however, there are marked differences among the warning sounds selected by various manufacturers. Additionally, there are considerable issues with LDWS working consistently in unfavourable environmental conditions. Both discrepancies in warning cue type and reliable system functionality may play a role in the effectiveness or ineffectiveness of LDWS. To date, little empirical research has been conducted to address these factors in currently implemented LDWS designs. In identifying the most common cueing format and potential reliability issues, the current thesis aims to systematically investigate potential problematic inconsistencies among LDWS. In addition, I will address a commonly overlooked topic in ADAS research- how LDWS impacts the performance of older drivers. To assess these factors, a simulation-based experiment will be conducted.

1.2 Sensory Cueing in Driving Automated Systems

Visual cues have been widely integrated among ADAS in the form of dashboard icons, flashing lights, and informational displays. While these cues are useful in comparison to control groups and for information rich ADAS, such as navigational maps, there is growing concern with their use as a primary warning signal. Given the importance of visual feedback from the road environment to operate a vehicle safely, visual icons may pose risk to drivers by averting gaze away from the roadway and/or may cause confusion (Klauer et al., 2006; reviewed in Visvikis et al., 2008). One study showing the resultant impact of this gaze aversion is by Peng, Boyle & Hallmark (2013), who showed that eyes-off-road time correlated with a significant increase in

standard deviation of lane position. As such, visual cueing, especially for LDWS, is likely not the safest option as a warning modality.

Vibrotactile cues have been of recent interest for ADAS which aim to redirect visual attention to potential dangers, such as rear-end collisions. Use of directional and non-directional vibrations in the driver seat, steering wheel or seat belt have been investigated, and results have shown these cues produce fast reaction times and effective re-direction of visual attention (Ho, Reed, & Spence, 2006; Ho, Tan, & Spence, 2005; Scott & Gray, 2008). Implementation of vibrotactile cues, however, faces challenges, as studies have shown varied individual response to motor priming cues, which may negatively interfere with driving performance (Hoc et al., 2006). Considering this lack of continuity between drivers' responses, there is apprehension that these cues will interfere with motor control during the driving task, and thus, vibrotactile cues have not been as widely integrated in ADAS.

Audio cues in ADAS have shown to be effective and efficient warning signals, demonstrating pronounced advantages in reaction time and overall driving performance over visual cues (Liu, 2001; Spence & Driver, 1997; Wickens & Seppelt, 2002). Audio warning cues have shown effectiveness in alerting drivers without competing with other important auditory information or other sensory cues. Audio cues are widely integrated in a variety of formats throughout different ADAS types. Despite this work, however, there is still disparity amongst which cues the research is showing to be effective, and what vehicle manufacturers are actually implementing. For LDWS, a basic review of patents and model features reveals audio cueing as the most commonly

integrated mode of warning signal. This thesis aims to identify the effectiveness of two different types of auditory cues across drivers of different ages. In order to identify the factors which may affect a cues effectiveness, we must first review how auditory cues have been used in other ADAS thus far.

1.2.1 Audio Cueing in ADAS

Audio feedback from the driving environment plays a critical role in operator performance. In considering the use of audio cues as a primary warning method of ADAS, we must pay particular attention to the risk of saturating the sensory environment (Edworthy & Hellier, 2000) and creating confusion or distraction from the primary task (reviewed in Nees & Walker, 2011). Specifically, audio warning cues should be accurate and concise, while conveying clear indication of their alarm. Hence, there must be considerable scrutiny over the type of audio warning cue selected.

Types of Audio Cues: Successful auditory sensory processing is comprised of at least three fundamental elements: the ability to detect a sound, recognize differences between different types of sound, and identify meanings associated with specific sounds (reviewed in Nees & Walker, 2011). Detectability and discriminability comprise the basic properties of sounds, including elements of frequency (Hz), intensity (dB) and rhythm. Research has shown favour for mid-range frequencies with regards to response time and driver preference in LDWS (Lin et al., 2009), and several studies have investigated the impact of spatially orientating to audio warnings in ADAS, with ongoing discussion regarding which alarm scheme is best (Cummings, Kilgore,

Wang, Tijerina, & Kochhar, 2007; Spence & Driver, 1997). The acoustic properties of audio warning cues are relatively objective and once optimized can be generalized. On the other hand, identification, or meaningfulness of audio warning cues is quite subjective and thus more complicated to implement. While sound engineers work to optimize acoustic properties, like detectability and discriminability, researchers have begun to explore the role of sound cue identifiability in affecting driver performance.

Research has shown that audio warning cues can improve driver performance, regardless of whether the sound is associated with a particular meaning (Spence & Driver, 1997). However, there is indication, from a sensory processing perspective, that sounds with ecological meaning may be superior to abstract cues in alerting drivers to danger. Two types of non-verbal auditory cues are commonly used in ADAS: earcons and auditory icons. The main difference between these cue type is their level of identifiability; earcons are abstract cues without distinctive meaning or symbolism (e.g. tones and beeps), while auditory icons are symbolic representations with meaningful association to their referent event (e.g. car horns or rumble strips) (Edworthy, 1994; Gaver, 1986; Gaver, 1989).

In ADAS, earcons can take the form of beeps, tones, or chimes played in repetition to alert attention to an event (Blattner, Sumikawa, & Greenberg, 1989). Earcons are particularly useful in audio-rich environments as they are not prone to masking due to their striking difference from natural sounds (Parker, Eberle, Martin, & Mcanally, 2008). However, their lack of identifiable meaning suggests a training period may be required in order for the cues to be most effective in order to familiarize the user to their cause and effect. Audio icons used in ADAS are usually

presented as the sounds of naturally occurring driving events, such as car horns, rumble strips, skidding tires etc. These sounds are similar to the events that they represent, similar to the concept of onomatopoeic words; symbolically represent a well-known concept based on social constructs, such as the sound of sirens to indicate police; or metaphorically resemble a similar process, like the sound of crumpling paper when dragging items to the trash on a computer (Bhat & Lai, 2013; reviewed in Blattner et al., 1989). The audio icons selected in ADAS are usually based on the purpose of the system. For example, some front collision warning systems use the icon warning sound of a rear-end car crash to alert the driver of approaching danger. In contrast to earcons, audio icons are inherently meaningful and are assumed not to require a training period, however their naturalistic characteristics may leave them prone to masking/ blending with environmental sounds.

Comparative research among audio icons and earcons has revealed favour for each sound type depending on the task at hand. In the field of flight simulation, both earcons and icons have been shown to produce similar performance results in specific flight training tasks (Meyer, Wong, Timson, Perfect, & White, 2012). In the driving context, both types of audio cues have shown better performance outcomes than other independent modalities, and work has shown both earcons and icons can improve driving performance (Spence & Driver 1994; Tobias, Su, Kolburg, & Lathrop, 2013). In a simulator study by Belz, Robinson, & Casali, (1999), a collision warning system was tested using tones in comparison with auditory icons (skidding tires or car horn) in isolated or supplemental visual display conditions. They saw that auditory icons induced faster braking times than tonal warnings, control conditions and an isolated visual condition (Belz, Robinson, & Casali, 1999). McKeown, Isherwood, & Conway (2010)

investigated the effectiveness of earcons (zapping pulses), icons (screeching tires), an environmental sound (gunshots), speech, and visual cues to alert a driver to hazards of front collision warning in a fixed-base simulator. The authors hypothesized that cues with a stronger ecological relationship between the cue and its meaning would act as “occasion setters”, priming the driver to react in a more appropriate way. Results showed the icon cue lead to faster braking responses in majority of comparisons, with equal results with the earcon and environmental cue in the other comparisons. Overall, the study suggests icons are a preferred cue for time-sensitive applications (Mckeown, Isherwood, & Conway, 2010). Further, Larsson et al. (2013) recently showed that auditory icons elicit faster braking times compared to earcons in collision warning ADAS, and that emotion is linked to behavioural response to sound cues (Larsson et al, 2013). Similar results have been echoed in a study comparing visual and auditory cues with high or low identifiable meaning in high or low workload conditions (Stevens, Brennan, Petocz, & Howell, 2009).

Through the works above, we see promising results for the use of icons over earcons, however, an interesting point of contention is noted in the risk of a possible trade-off between response speed and response accuracy. In a study by Graham (1999), four audio cue types were tested in a computer monitor-based simulation, where a front collision warning system featured both true and false alarm conditions. Braking times were significantly faster with icon warning cues, but accuracy was sacrificed such that the number of presses was significantly higher in false alarm conditions (Graham, 1999). Similar results were documented by Ho and Spence (2005).

Recently, Gray (2011) used a full scale driving simulator to assess effectiveness of warning sounds with rising intensity (looming) in a rear-end collision scenario with true and false alarm

conditions. Gray (2011) showed that looming warnings elicited the best combination of response speed and accuracy, even over an icon sound. This suggests meaningful changes in cue intensity, rather than cue type, may play a role in how quickly and appropriately drivers respond to audio stimuli (Gray, 2011).

As seen in these studies, there is still discussion over audio cue selection for ADAS as both cue identifiability and acoustic properties may influence how effective a system is at enhancing driver response. Importantly, while research has explored audio cue types in several types of ADAS (e.g. collision warning systems, blind spot detection, etc.), only a few studies have investigated the use of audio cue warning platforms specifically in LDWS. This is important given that in addition to acoustic properties and identifiability of auditory cueing in LDWS, the intended *purpose* of the warning system should be considered when selecting which cue should be used. Thus, the current thesis focuses on comparing the effectiveness of exemplar earcon and icon cueing implemented specifically to support lane keeping.

1.2.2 Audio Cue Warnings in LDWS

Research in LDWS has, for the most part, focused on the effectiveness of cue modality (e.g. visual vs. tactile vs. audio) rather than specific cue identifiability characteristics within a certain modality (e.g. *types* of audio cues). For example, Kozak (2006) investigated the use of wheel torque, rumble strip sound, wheel vibration, and head-up displays in LDWS used by drowsy drivers, finding torque and vibrational cues elicited faster reaction times and better lane keeping performance (Kozak et al., 2006). Other work has investigated the bimodal use of audio and

haptic warnings in LDWS and LKS, showing effectiveness for both unimodal cue types and most significant effects for bimodal (combined) cue types (Navarro et al., 2007).

Audio specific work in LDWS has been fairly limited to investigations of spatial orientation and manipulations of the same audio cue, as opposed to comparison of different audio cue types. Cummings et al. (2007) used bidirectional and unidirectional audio warnings with high reliability (3:1, true-positive: false-positive) or low reliability (1:3, true-positive: false-positive) in distracted drivers presented with collision event types (front, rear, lane departure). Their results indicated no significant difference between alarm schemes in affecting driver response time (braking or steering action) or accuracy (appropriate response to true or false cue). Others have compared a single rumble strip sound vs. rumble strip plus beep sounds and showed similar effects on driver reaction time and lane keeping performance (Rossmeier et al., 2005). A study by Suzuki and Jansson (2003) compared two types of audio cues (mono vs. stereo beep) finding no significant difference in reaction time. In one recent experiment audio cue type effectiveness was studied with regards to LDWS: Fung et al. (2007) investigated the effect of speech vs. beep warning cues on perception-reaction time, speed, and lane keeping in a simulation experiment. Their results indicated better lane keeping with the beep cue and better perception-reaction brake time, overall, with a warning system- regardless of audio cue type. Another study evaluated the satisfaction ratings with self-selected audio cues from a list of 162 non-meaningful sounds for LDWS, finding highest satisfaction and acceptability with a low frequency rumble cue (Fagerlonn, 2007).

Reviewed in the introduction of this thesis, we see that audio cues are a commonly integrated warning type in LDWS, but research regarding the efficacy of audio cue types has been relatively unexplored. Considering the promising, yet sometimes divergent research findings seen in the context of audio cueing used for other types of ADAS, there is reason to hypothesize that icons and earcons may produce differing lane keeping performance when used specifically in a LDWS. To address this gap, the experimental design of this thesis focuses on the comparison of an earcon and icon cue on drivers' lane keeping behaviour. The icon cue chosen for the study was a rumble strip sound due to its reference to real rumble strips that are used on road shoulders to alert drivers to unintended lane departures. The earcon cue chosen for this study was a beep cue sound due to its common use in integrated LDWS and lack of meaningful referent. (Further discussion in Ch. 5) In addition to exploring the effectiveness of each of these cue types overall and better understanding how inconsistencies among LDWS cueing mechanisms may affect driving responses, we can also specifically evaluate how these factors uniquely impact older and younger drivers.

1.3 Adaptation to Driving Behaviours

Behavioural adaptation in the context of driving can be defined as the altered performance of a vehicle operator following a specific change in the road-user-vehicle system; said alterations may have a positive, negative, or neutral effect on driving performance (OECD, 1990; Rudin-Brown & Noy, 2002). Research in this area has emphasized the importance of trying to identify the predictors and outcomes of behavioural adaptation with particular consideration for those which may induce positive or negative changes to driving performance. However, identifying these factors is difficult as behavioural adaptation is inconsistent and may differ in magnitude

and direction depending on the technology and its user (Saad, 2006). In order to interpret how LDWS induce behavioural adaptation in drivers, we must first briefly review the fundamentals of adaptation in driving.

1.3.1 Factors Associated with Adaptation

One of the first well-known driving adaptation theories was developed by Wilde (1982), suggesting that drivers consistently strive to find a homeostatic balance between a personally acceptable level of risk and the probability of achieving certain driving goals (Wilde, 1982). In order to achieve these goals, drivers must consider their maximum acceptable level of risk versus the currently perceived level of risk and adjust their behaviour accordingly. If perceived risk outweighs the personal maximum, a driver will modify their behaviour to lower the risk level to within the personal maximum limits. Conversely, if the currently perceived risk is within the personal maximum, a driver can adjust their behaviour to accept higher perceived risk in order to achieve their driving objectives (reviewed in Breyer et al., 2010). This theory suggests that automated systems alter a driver's perception of risk continuously throughout driving and as a result, their behaviour. Built on this concept, risk-based theories for driving behavioural adaptation have been expanded (Fuller, 1984). Within this theory, however, there is controversy over methodological issues in that the development of a driver's subjective and target risk levels cannot be clearly defined.

Rather than a constant balance of perceived vs. actual risk, Näätänen & Summala theorized that subjective risk is at a zero level in normal driving tasks out of habituation (Näätänen & Summala, 1974; Summala, 1988). Specific driving events, which fall outside of the subjectively perceived safety margin, will elicit a non-zero response. The driver's risk-related behaviour may then be shifted through adaptation such that zero-risk levels become relative to the adapted level (Näätänen & Summala, 1974; Summala, 1988). For example, when a driver first gets behind the wheel their subjective risk associated with speed is zero at slow speeds. However after exposure to faster speed when driving on, say, a highway, they behaviourally adapt and shift their zero-risk level to a higher speed than when they first began. This is why speed limits are important as they decrease the tendency for drivers to become adapted to higher speeds as their baseline zero-risk level. Considering this theory, ADAS may alter the driving task such that the awareness of risk is more salient and thus drivers become adapted to higher-risk events as the new zero-risk level.

Alternative theories with emphasis on driving environment and nature of the automation system have been investigated. For instance, Evans (1985) suggested that feedback plays a significant role in prompting behavioural changes, such that clear, consistent feedback between user and technology promotes adaptation. Other research suggests demographics and trip information, such as trip location and drive time, may play a significant role in driver's adaptation to ADAS, along with road intricacy and the driving environment itself (Rosenfeld et al., 2012; Rudin-Brown, Edquist, & Lenné, 2014). In each of these cases we see higher adaptation potential with ease of use, such that, if ADAS is interactive and helps alleviate complexity of the driving task,

users are more likely to use and adapt to the use of the system by displaying altered driving behaviours with respect to the system's functions. This concept was used to develop the experimental methodology for this thesis; a challenging course design was selected for the driving task in order to best evaluate adaptation effects across different audio cue types and driver populations.

Importantly, a thorough body of work has been developed in examining the role of driver characteristics and emotional factors that may affect adaptation. One of the most heavily studied factors of adaptation has been the concept of trust. From a broad sense, the more we trust our automation system, the more likely we are to use it and rely on it, and thus our driving behaviours adapt accordingly. Lee and Moray (1994) first explored trust in automation through components of compliance (using an ADAS appropriately and frequently) and reliance (assuming the ADAS is providing appropriate feedback even though it may not be) (Lee & Moray, 1994; Muir, 1994). It was also shown that use of automation is high when users trust the system and this positively correlates with the amount of time a user has spent with the system (Muir & Moray, 1996; reviewed in Rajaonah, Tricot, Anceaux, & Millot, 2008). Additionally, work has explored trust in conjunction with self-confidence, mediated by workload and perceived risk factors, suggesting that high self-confidence and low trust will lead to manual task completion, while high trust and low self-confidence will lead to reliance on automation (Lee & Moray, 1994; Riley, 1994). More recently, Stanton and Young (2000) have outlined the importance of system reliability and predictability as a foundation for trust. As users see consistent reliability and predictability, trust increases and users begin to adapt and allow the

system to take on certain driving tasks. Interrelated with trust, driving motivations (Summala, 2007), mental workload (Cantin, Lavallière, Simoneau, & Teasdale, 2009; Recarte & Nunes, 2003), situational awareness (Gugerty, 2011), and personality traits (Rudin-Brown et al., 2014) have each been evaluated as individual contributors to adaptation.

In addition to the increased trust and perceived risk that may accompany use of LDWS, perceptual-motor coupling may also have an impact on driver adaptation. For instance, the sensory feedback that is provided through cueing systems helps to coordinate appropriate motor response (i.e. steering/braking) (Crespo & Reinkensmeyer, 2008) associated with changing vehicle dynamics. This mechanism is critical given that it occurs at a pre-conscious level and can affect the type of rapid, reflexive responses required in the context of behavioural correction during driving. In the context of using LDWS, consistent feedback on lateral position of the lane boundaries is communicated to the driver when they deviate too far from the center of the lane. This feedback could trigger faster motor reflexes than would be normally be initiated without a warning system. Repetition of this altered perceptual-motor coupling could then become ingrained as an adapted reaction to use of LDWS.

It is clear that behavioural adaptation is a multifaceted entity with both technology and driver factors affecting how and in what capacity it may occur. As seen above, there are features of risk-perception, perceptual-motor coupling, system/environment nature and other driver characteristics that play a role in behavioural adaptation to ADAS. However a comprehensive

understanding of how the combination these factors influences the adaptation is still under discussion.

1.3.2 Positive vs. Negative Adaptation

Behavioural adaptation to the use of automated systems may have the potential to greatly improve driver performance for specific tasks. Positive adaptation effects have been shown in various studies when systems are reliable and frequently used. For example, LDWS has shown improved use of turn signalling as an unintended benefit of system use (Alkim, 2007; Portouli et al., 2006) and adaptive cruise control has been shown to promote efficiency in merging strategies (Hoedemaeker & Brookhuis, 1998). From a common sense perspective, it is conceivable that warning aids can greatly improve our performance, and this performance level can be maintained when the aid is removed. Through warning feedback, LDWS may train drivers to intuitively become more aware of their vehicle's lateral movement and thus, if the LDWS is removed, the driver's ability to maintain road position may, in fact, be better. A fundamental issue with this concept is that, for many people, driving is an already learned task. As a function of the fact that many people have learned to drive without automated systems, the new addition of these systems suggests there may be need for a training period where drivers re-learn the task while using the automated system. Research has shown training with ADAS can improve driver performance (Maltz, Sun, Wu, & Mourant, 2004), and as a result positive behavioural changes may follow.

Contrarily, behavioural adaptation may have the potential to lead to misuse and disuse of automated driver assistance systems. The risk of negative effects on driving performance is a

critical area of research in behavioural adaptation to automated driving systems. With automation aimed at replacing some of the driver's workload, there is less opportunity for a vehicle operator to practice their driving skills. A lack of practice may lead to discomfort or complacency and therefore greater reliance on the automation system (Parasuraman & Riley, 1997). This cycle, in which automation misuse is perpetuated, exhibits an ironic effect, best put by Lee (2008), pg.407: "automation aimed at replacing the human often has the effect of undermining performance because it leaves people unsupported in accommodating the situations that the automation cannot accommodate". The propensity for LDWS to create a cycle of negative behavioural adaptation is concerning. With greater use of LDWS, an operator may become complacent in monitoring the lateral movement of their vehicle. Disuse of this skill may later affect their ability to identify and effectively mitigate a dangerous situation if the automated system fails, such as in visual sensor based LDWS which may be unreliable in locations with obstructed lane markings. Alternatively, there may be risks of over-trust where a driver simply believes their system is accurate even when it may be faulty. With these concerns in mind, several studies have attempted to investigate whether or not lateral control assistance systems promote negative behavioural adaptation.

1.3.3 Negative Adaptation with Lateral Control Systems

The way in which a driver's behaviour may be affected by automation is a multi-faceted issue and a consistent subject of studies focused on the use of ADAS. However, to date, there is a limited body of research dedicated to examining the effect specifically in LDWS/LKS. The concept was investigated by Breyer et al (2010) in a field experiment where participants drove

with a reliable (consistently active) and unreliable (intermittently active) LKS while completing a secondary task to explore the potential for negative adaptation. The findings from this study suggested that even after prolonged use, there was no significant difference in driving performance between the reliable and unreliable conditions. Moreover, there was no evidence to suggest the system provoked a change in fundamental driving style, as the lateral control and maximum speed values showed no difference between conditions. The authors concluded that their participant population appeared to appropriately judge the reliability of their system and there was no indication of negative behavioural adaptation with use of an LKS (Breyer et al., 2010). Similar findings were seen in a 15-week field study by Portouli (2006) where LDWS and a front collision warning system were examined independently and in combination. Results showed that the LDWS decreased standard deviation of lateral position, and had significantly less trigger events compared to baseline- further investigation revealed that drivers tried to avoid triggering the LDWS when it was used in isolation, but did not do so when the LDWS was used in combination with other systems. In addition, the authors found that warning system presence lead to higher average driving speed, but concluded no negative behavioural adaptation effects were seen (Portouli et al., 2006). Another study looked at LDWS using four alert modalities in a 4-week field experiment, finding significantly better performance with LDWS active compared to the first week where baseline measures were collected, and no indication of negative adaptation (LeBlanc et al., 2006). Popken (2008) evaluated various levels of lateral assistance in a driving simulator. Participants drove with either high automation (LKS), medium automation (LDWS), or no automation and were asked to complete a secondary visual task. While results did not specifically address lane-keeping effects, they showed no significant difference among

groups in gaze aversion behaviours throughout the drives (Popken, Nilsson, & Krems, 2008).

Across these works, periods of system unreliability and secondary tasks were used to investigate possible behavioural adaptation effects of LDWS, showing no inclination of negative adaptation.

While the studies above suggest lateral control systems may not influence the likelihood of behavioural adaptation, inconsistencies remain. A well-cited study by Rudin-Brown and Noy (2002) demonstrated differential effects of behavioural adaptation related to psychological characteristics of individuals (trust, locus of control, and sensation seeking personalities).

Employing a reliable and unreliable LDWS in a simulator and closed-track driving test, the study showed that less sensation-seeking and more external personality types were more likely to trust the automated system. Further, the only participants who made full lane departures when the system failed to provide warnings were those who reported trusting the LDWS. The authors concluded that systems like LDWS should be used with caution as they may potentiate over-trust. While an analysis of psychological characteristics was outside the realm of this current thesis, questionnaires regarding driver personality type and comfort (see section 3.1 Protocol) were administered for future analysis and correlation to the findings of this work.

1.4 Older Drivers

With a limited pool of work and disagreement among findings, the investigation of lateral control systems and behavioural adaptation is far from over. Previous work has used varying course designs or field tests to observe adaption effects, however, the sensitivity of these outcome measurements may not be strong enough to detect more subtle changes in driving

behaviour. Moreover, there has yet to be a highly controlled study that solely manipulates LDWS reliability and a highly detailed analysis that directly compares performance of aftereffects with system use. In the following study, we attempt to build on the current body of work and further explore the potential of behavioural adaptation to LDWS by conducting a controlled simulator study with directly comparable track performance in LDWS under reliable and unreliable conditions. Further, we seek to explore if there are differences among driver age populations, which may affect the magnitude and direction of said adaptation. In less than ten years, it is predicted that one in four people will be over the age of 65 years old in most OECD countries (OECD, 2011). Within Canada alone, seniors represent 13% of the total population, a statistic attributed to various factors such as aging of the baby boom generation, advances in medical care, and declining birth rate (reviewed in Eby & Molnar, 2009). As this number rapidly increases, so does the number of older drivers. Currently, there are around 3 million people over the age of 65 with a driver's license in Canada (Turcotte, 2012). For older adults, driving is a means of accessing basic necessities and dramatically impacts a person's sense of freedom, independence, self-esteem, and overall quality of life (Charlton et al., 2006; Dellinger, Sehgal, Sleet, & Barrett-Connor, 2001). The loss of a license or ability to drive can have significant physical and emotional consequences. From a practical standpoint, inability to drive leads to dependence on others or public transit, which may encompass further issues such as lack of accessibility, unreliability and safety hazards. From a mental well-being standpoint, the loss of a license has been linked to feelings of isolation, decreased social participation, and depression (Marottoli et al., 2000). In light of these obvious detriments, it is important to help healthy older

drivers stay on the road as long as possible, while also prioritizing their safety and the safety of others.

Older drivers are overrepresented in serious crash injury statistics; in Canada, older drivers make up 16% of total crash fatalities and 8% of injuries in all vehicle collisions (Transport Canada, 2011). While overall, older drivers' crash rates are, in fact, lower than their younger counterparts, per kilometer, their crash rates remain higher (Braver & Trempe, 2004; Li, Braver, & Chen, 2003). Moreover, following an accident, older drivers are four-times as likely to be hospitalized, are more likely to suffer severe injury, and have a higher chance of death (Li et al., 2003). While many factors may contribute to the increased risks for older drivers, such as decreased resilience to trauma and injury, recent inquiries have shown links between driving performance and age-related changes (O'Neill & Dobbs. B.M., 2004; Vaa, 2003).

1.4.1 Older Adults and Cognitive and Sensory Deficits

Driving is a complex cognitive task, requiring the rapid integration of various sensory stimuli along with dynamically changing environmental factors. As we age, gradual changes are seen in cognitive and perceptual processing such as, informational processing speed, sensory sensitivity, attention and memory; and these changes can greatly impact driving performance and comfort (Aksan et al., 2012; Schall et al., 2012; reviewed in Simoes, 2003). Despite these changes, older drivers are able to maintain good driving performance through self-regulation, exercising caution, and using ingrained experience-based skills to compensate for functional deficits (Ball & Owsley, 1991; Charlton et al., 2006). In the past, integration of automation for older drivers

accompanied concerns of generation effects, lack of experience with technology (Kelley & Charness, 1995), rejecting the system, steeper learning curves, and/or added complexity to the already challenging task of driving. And while these concerns are still relevant, more recently research has shown older drivers as one of the highest consumer populations of ADAS equipped vehicles, indicating willingness to use automated systems for driving support (reviewed in Yang & Coughlin, 2014; De Waard, Van der Hulst, & Brookhuis, 1999). Vehicle automation systems have the potential to compliment these skills by enhancing cues and providing further resources to compensate for possible deficiencies. Conversely, automation systems have the potential to remove the familiarity component of the driving task, counteracting the benefit of an older driver's experience-based skill set (see section 1.4.2). While cognitive and sensory changes associated with aging are well documented, a limited amount of research has been conducted to study the impacts of automated driving systems on older drivers and the specific relationship with cognitive and sensory deficits. Some results suggest benefits where a well-designed automation system can reduce the amount of sensory processing required from the driver, leading to overall improved performance (reviewed in Baldwin, 2002; Llaneras, Lerner, Dingus, & Moyer, 2000). For example, in a study by Dotzauer et al. (2015), an automated assistance system showed positive results for advising older drivers when it may be best to traverse an intersection. With the potential benefits and risks in mind, as well as the fact that older adults are a main consumer of ADAS (due to financial capability and perceived need), it is imperative to consider the automation design and which sensory cueing features are best suited to help, not hinder, older drivers.

For older drivers, lane keeping is a particularly challenging task which can be exacerbated by factors of ageing, such as cognitive decline. For example, studies looking at cognitive impairment in older drivers have found lane position control errors (deviations) and lane violations to be the most common errors among drivers with mild/ non-advanced Alzheimer's (Dawson et al., 2009) and Parkinson's disease (Uc et al., 2009). While these two diseases are on the more extreme end of cognitive impairments, similar challenges with lane keeping have been seen in healthy older adults when compared to younger drivers, particularly on roads with complex road geometry (Merat, Anttila & Luoma, 2005). A variety of work has been completed looking at the effects of increased cognitive workload through secondary tasks on older adults' driving performance. Son, Lee & Kim (2011) used a fixed-based driving simulator to assess driving performance in older and younger drivers when presented with a secondary auditory recall task on urban and highway courses. Interestingly, the lane keeping results for older adults revealed that under increased cognitive load, standard deviation of lane position showed improved lateral control, however, steering wheel reversal rates indicated poor lateral control. The authors concluded that older drivers showed greater vulnerability to increased cognitive workload through their increased steering correction movements when presented with the secondary task (Son, Lee & Kim, 2011). Similarly, Son et al. (2010), saw significant reductions in lateral variation and velocities for older and younger drivers when presented with a secondary task, and Merat et al. (2005), found greater lane keeping control on non-complex road sections during concurrent performance of an auditory memory task. When considering the addition of ADAS to vehicles for older drivers, the effect on cognitive workload and sensory processing is critical. While these studies indicate increased cognitive workload may increase lateral control,

secondary factors, such as increased steering wheel corrections gives greater insight as to how the additional task load is being processed and prioritized.

The modality of cueing used in automated driving systems may play a critical role in its successful implementation and use by older drivers. As reviewed in Section 1.2, interface designs that use an audio and/or haptic cueing system elicit better driving performance results over visual warning methods. In the case of older drivers, recent work has suggested that multimodal displays (audio-visual or audio-haptic) may lead to the greatest benefit (Spence & Ho, 2008). Audio cues have been shown to provide adequate warning without overloading or distracting the driver, and have also shown significant positive impact on driving performance during simulation experiments (May, Baldwin, & Parasuraman, 2006). With these promising results, we must not forget that there are both structural and functional changes in hearing associated with ageing which must be accounted for in the design of audio cue systems (reviewed in Baldwin, 2002). With ageing, sensitivity to high frequencies lessens and ability to differentiate between sounds may be impaired (reviewed in Baldwin, 2002). Thus, in using audio cueing systems, the signal-to-noise thresholds must be evaluated to ensure older adults can successfully detect and differentiate between cues and background noise. In the design of audio cue systems, the type of audio cue used may be of great impact to older drivers, affecting their ability to understand and appropriately react to cues. In the current thesis, the effectiveness of audio cue types in healthy older drivers will be specifically addressed to evaluate whether performance outcomes are linked to inherent understanding of a warning sound. Older

participants used in this study were screened for basic sensory and cognitive deficits (further described in Ch. 3) in order to most effectively evaluate the impact of the audio cue warnings.

1.4.2 Adaptation in Older Adults

In conjunction with evaluating the effectiveness of audio cue types for older drivers, there is particular interest in observing any adaptation effects, which may arise from their use. As briefly mentioned earlier, automation systems may be highly useful in creating a more comfortable, safe driving experience for older drivers. However, there is also risk of distraction, confusion (Maltz et al., 2004) and possible higher susceptibility to negative adaptation effects. In this negative adaptation, older drivers may become overly reliant on their automation system and lose previously practiced-skills, which may be necessary should the automation system prove faulty (reviewed in Reimer, 2014). In the same study by Dotzauer et al. (2015) mentioned previously, along with positive effects on intersection driving performance came unintended carry-over effects. Specifically, following a period of use with intersection assistance technology, older adults were shown to spend less time checking left and right during the same task when the automation system was no longer active (Dotzauer et al., 2015). This example displays the possibility that the use of ADAS in older adults may amplify negative performance aftereffects, more so than what is seen in younger drivers. Considering the potential for unintended behavioural changes, which may increase safety risks, and lack of current research dedicated to the topic, there is evident need for focused research in the effects of automated systems on older drivers.

Throughout this chapter, a survey of the literature shows a lack of understanding of audio cue effectiveness, and adaptation in LDWS and its manifestation in different ages of driver populations. In the following experiment, we will address some of these gaps through an experiment evaluating the effectiveness of icon and earcon audio cues in lane keeping performance. In order to effectively observe these effects, controlled manipulations of the driving task were required – a requirement best met by the use of motion simulation.

1.5 Use of Simulation in Driving Research

The use of simulators to conduct driving research has significant advantages to study factors related to auditory cueing in LDWS. First, simulators provide the unique opportunity to maintain a high level of control over experimental factors. In a real driving condition, uncontrollable variables such as the environment (e.g. weather), surrounding traffic, vehicle in use, etc. are in play. In a simulation environment, we have precise control over all factors of the driving environment and vehicle. For example, all subjects drive the simulator in the same vehicle model, with the same eye-height, size, sensory feedback, environmental conditions, and visual surroundings.

Second, simulation allows us to appropriately challenge drivers in a controlled and safe manner, which would otherwise be dangerous on real roads. Specifically, in this study, a complex, winding course was used to intentionally challenge drivers on their lane keeping ability. Its complexity allowed for a highly-specific observation of realistic lane departures which may otherwise be unnoticed in a field experiment due to lack of system sensitivity, lack of

measurement capabilities of specific driving parameters, and/or availability of controlled and sufficiently challenging driving conditions.

Third, the objectives of this experiment call for minute manipulations of auditory cue types (earcons and icons) and strategic control of system functionality to observe adaptation effects (i.e. intermittently turning the cueing system on and off). These specialized manipulations, which would be difficult to regulate in a field test, can be effectively accomplished using simulation technologies. While simulation also has its drawbacks (discussed in Ch. 6), for this particular experiment it gives us the greatest opportunity to observe effects and control for possible confounding variables.

1.6 Motivations for this Research

Over the course of this literature review, the rise of automation in in-car technology assistance systems has been reviewed, with particular focus on LDWS. Debate over the effectiveness of LDWS has been underway since their inception, however, recent statistics from the IIHS suggest LDWS, in fact, may play a role in perpetuating crashes. While the reasoning for these statistics is unknown, several potential sources of issue have been brought to light. A thorough review of the current body of literature surrounding effectiveness of LDWS in driving reveals several gaps. First, there is limited fundamental understanding of the effects of audio cue type on lane deviation behaviour of a vehicle operator. There is no standardization across vehicle manufacturers to outline which type of audio warning should be used in LDWS. Two common types of audio cues, earcons and icons, display very different properties of detectability,

discriminability, and identifiability. As such, there is need for investigation as to which, if either, of these audio cue types is most appropriate for use in LDWS.

Second, there is increasing controversy over the possible behavioural adaptation effects associated with using assistance systems such as LDWS. Adaptation effects are complex and variable amongst drivers, and there has been work implying both neutral and negative adaptation effects to use of LDWS. Considering the issues with system reliability (when lane markings are not visible), and potential for over-reliance and over-trust, adaptation effects must be considered with particular scrutiny. Moreover, recent work has yet to complete a detailed analysis on LDWS use, where LDWS functionality is not confounded by environmental variables in on-road conditions (e.g. car type, traffic, time of day). Therefore, a more sensitive analysis and design methodology is required to evaluate potential adaptation effects of LDWS.

Third, the effects of different types and properties of audio cue LDWS on the driving performance of older drivers are not well understood. Older drivers are largely excluded from complex driving experiments due to their challenging recruitment, eligibility, and high dropout rates. Resultantly, the effects of LDWS have not been thoroughly investigated in older drivers. And with consideration for their possible decreased sensory and perceptual processing capabilities, there is significant reason to believe the addition of LDWS may uniquely affect older drivers in comparison to younger drivers.

In considering the staggering statistics surrounding vehicle-related deaths, increasing driver populations, and increasing older driver populations, the unknown effects of LDWS are concerning as they may have significant impact on many drivers. Building on these concerns

and the above-discussed gaps within the literature, a driving simulation experiment was designed to specifically evaluate the use of LDWS with different audio cue types in older and younger drivers.

Chapter 2

2.1 Research Objectives

To address the gaps in knowledge outlined in Chapter 1, a study was conducted to examine three primary objectives:

1. The first objective is to identify whether different types of audio cueing leads to better/worse lane keeping and how performance with audio cueing compared to driving without the use of a LDWS. Prior research has shown effectiveness in experience with cues to improve human performance in vehicle operator tasks. We aimed to build on these findings by observing how the use of two warning sound cues could affect driving performance. Considering the different categories of audio cue types most typically used in current vehicle warning systems, we selected one audio cue from each of two category types: an icon and an earcon. The first cue was selected to be an intuitive sound (icon) that a driver would naturally associate with the act of leaving one's lane, in this case, the sound of rumble strips. This cue was meant to be a sound that would be immediately meaningful to the driver, thus they could understand its association with deviating from the lane without prior experimental exposure to the cue. The second sound was selected to be a non-intuitive cue or that which would not inherently be associated with lane departure; in this case the sound of beeping.

2. Second, we aimed to evaluate the presence and patterns of short-term behavioural adaptation to the use of the different types of LDWS audio cues. As reviewed in the literature,

there is discrepancy among LDWS specific studies, with some studies showing no evidence of adaptation, while others have seen positive indication. However, there has yet to be a detailed analysis in a controlled environment where the only changing factor between conditions is the activity of LDWS (on vs. off). As mentioned in section 1.5, simulation provides the opportunity to manipulate details of the driving environment in order to evaluate subtle changes in driving performance. This experiment utilized simulation technology to evaluate the effects of intermittent removal of the audio cue warning system following a period of LDWS active driving. Specifically, trigger points that turned off the LDWS were placed approximately every 500 meters throughout the last driving course. Participants were not informed that the LDWS would be turned off during the drive and thus believed that they would complete the course with the LDWS activated at all times.

3. Third, we aimed to examine how the use of LDWS under different audio cueing conditions affected lane-keeping performance and adaptation in experienced older drivers (65+) compared to experienced younger drivers (18-35). To date, there has been no research to review the effects of LDWS on older drivers and how these effects may differ from younger drivers. Recognizing the typical differences in sensory and cognitive abilities between older and younger drivers it is possible that the same technology could uniquely affect driving performance between these two groups.

2.2 Hypotheses

In correspondence with the research objectives outlined above, several hypotheses were developed.

With vs. Without Audio Warning Cueing and Effect of Cue Type: With regards to the first research objective of this study, we hypothesized that, consistent with most previous findings, the immediate introduction of audio cueing would lead to better lane keeping than driving without a warning system. With respect to warning cue type, as seen in section 1.2.1, there is indication that meaningful audio cues that do not require training to build associations may provide useful information during initial exposure and thus lead to better operator performance (Bonebright & Nees, 2007; McKeown et al., 2010). Building off of these studies, we hypothesized that initially cues more naturally associated with lane departures (rumble strips) would lead to better lane keeping compared to other types of non-meaningful audio cues (beeps). However, following even a brief exposure to the system (less than 10 minutes), it was expected that both types of audio cues would be equally effective in reducing lane deviations compared to no system at all.

Adaptation Effects Following Previous Experience with the Audio Warning Cue: Across both age groups, it was hypothesized that following exposure (10 minutes) to the LDWS, there would be indications of behavioural adaptation regardless of audio cue type. As several studies have indicated with other ADAS, (e.g. collision detection warning systems) even short-term exposure can lead to unintended changes in driver performance (Dotzauer et al., 2015; Hoedemaeker &

Brookhuis, 1998). With exposure to the system, we predicted that participants would adapt; becoming more comfortable with the system use, and more comfortable with the human-vehicle-environment interactions. This behavioural adaptation was expected to have a negative impact on lane keeping behaviours in the final driving course when the LDWS was unreliable. In the sections of road where the LDWS was unexpectedly turned off, we speculated that due to their previous experience with the warning system, participants would show worse lane keeping performance in the absence of feedback compared to the same sections of road where the LDWS was turned on as expected.

Age-Related Effects Associated with Audio Cue Type and Adaptation: At baseline, it was expected that older adults would exhibit worse lane keeping than the younger drivers due to age-related deficits. It was predicted that the introduction of a LDWS would offset age-related sensory/cognitive declines, leading to overall increased lane keeping performance (frequency, duration and magnitude of lane deviations). Specifically, it was hypothesized that older drivers would be more heavily affected by the use of the LDWS; showing greater improvements in lane keeping with exposure to the system (relative to baseline) compared to the younger population. Older adults were also predicted to be more significantly affected by the intermittent removal of the LDWS.

Chapter 3

3.1 Methods

This research took place at the Toronto Rehabilitation Institute (TRI), University Health Network's intelligent Design for Adaptation, Participation and Technology (iDAPT) Centre for Rehabilitation Research. Ethics approval for the study was obtained via the University Health Network Research Ethics Board (REB # 14-7769).

Participants: Healthy participants were recruited through TRI and the local community using adverts in University Health Network hospitals and public venues. Participants were monetarily compensated \$10 per hour for their participation in the study. All recruited participants were screened via telephone interview to ensure eligibility. Eligibility criteria required them to be fully licensed drivers with greater than two years of driving experience and to be in good general health with normal/corrected-to-normal visual acuity and no clinically diagnosed levels of hearing loss. In addition, participants were required to fall within the age ranges of 18-35 for younger adults or 65+ for older adults. Pre-screening telephone interviews included basic medical history, driving experience, and completion of the Motion Sickness Susceptibility Questionnaire Short-form (MSSQ-S) (Golding, 2006) (Appendix 1). Eligible participants were then invited to TRI to take part in the study. Upon arrival, participants were asked to read and sign the study consent form and were given a copy of the form for their records. Participants completed a visual acuity test using the Snellen eye chart, required to achieve >20/40 in both eyes, and a hearing detection test in the simulator on a short pre-test drive with LDWS audio

cues activated. Throughout this short pre-test drive, without prompting, each participant was asked to identify when the warning cue had been triggered to confirm that they could successfully detect and identify the sound from the natural background driving sounds. Older adults completed the Montreal Cognitive Assessment Version 7.1 (MoCA) as a baseline measure of cognitive function and were required to achieve a score of >26 to continue in the study (Nasreddine et al., 2005).

There were 34 participants (24M, 10F) successfully recruited for the study. There were 8 older participants (5 M, 3F) and 1 younger participant (F) unable to complete the driving courses due to simulator sickness. This resulted in a sample size of 14 younger ($M=27.1$ years, $SD=4.9$, $range=22-35$) and 11 older adults ($M=72.3$ years, $SD=6.4$, $range=65-87$).

Stimuli & Apparatus: At the center of the iDAPT facility is the Challenging Environment Assessment Lab (CEAL), which features a 6 degrees-of-freedom hexapod motion base with interchangeable payloads (Figure 1). This study utilized the active motion base with the StreetLab payload, which was outfitted with a fully immersive, multi-sensory driving simulator, with 240° field-of-view horizontal and 90° vertical curved projection system and realistic audio soundscape. The StreetLab driving simulator was comprised of a steering wheel, brake pedal, gas pedal, dashboard and windshield (Figure 2).



Figure 1: CEAL 6-axis motion base. Pictured is the hydraulic based motion system, with interchangeable payload.



Figure 2: StreetLab car mock-up. Pictured is the driving view from inside the StreetLab car mock-up.

OKTAL's SCANer™ studio driving software was used to create high-resolution simulations for the driving tasks. Prior to experimental conditions, a practice drive was completed on Course 1 (Figure 3), which featured a basic, relatively flat 4-lane highway course with gentle curves and sparse traffic. The speed limit for this course was suggested as 80km/hr. All participants drove the same Course 1 for acclimatization. Experimental conditions utilized Course 2 (Figure 4), which featured a more complex 2-lane curvy mountain course with sharp turns, sparse traffic, and a visual seasonal change (summer-winter). The speed limit for this course was suggested as 50km/h on straighter sections and 30km/h on hairpin curves.



Figure 3: Course 1 from OKTAL SCANeR™ studio software. Bird's-eye view of the basic flat course shows the driving route highlighted and gentle curves for easy acclimatization. Speed limit over the total course was suggested as 80 km/h.



Figure 4: Course 2 from OKTAL SCANeR™ studio software. Bird's-eye view of the curvy mountain course with 5 hairpin curves shows the driving route highlighted. Speed limit on straighter stretches was marked as 50 km/h and 30 km/h on hairpin curves.

Two sound cues were used in the triggering of the LDWS. Group 1 was given the continuous sound of repeated beeping: 360 ms recording containing three tones; at approximately 2500 Hz and a secondary beep at approximately 1700 Hz (Figure 5). Group 2 was given the continuous sound of repeated rumble strips: 2s recording, containing four rumble pulses; a lower frequency broad spectrum sound, with most of the power in harmonics of approximately 90 Hz up to 1000 Hz (Figure 6). Decibel levels for each sound cue at rest, and in combination with engine sounds ranging from coast to throttle are summarized in Table 1. Audio cues were triggered to turn on using distance values from the front right and left wheels. When the front right or left wheel of the vehicle touched the inner boundary of the left lane marking or right road boundary, the alarm would sound and play continuously until the wheel returned to fully-within the lane; a similar strategy to many patented LDWS currently in use.

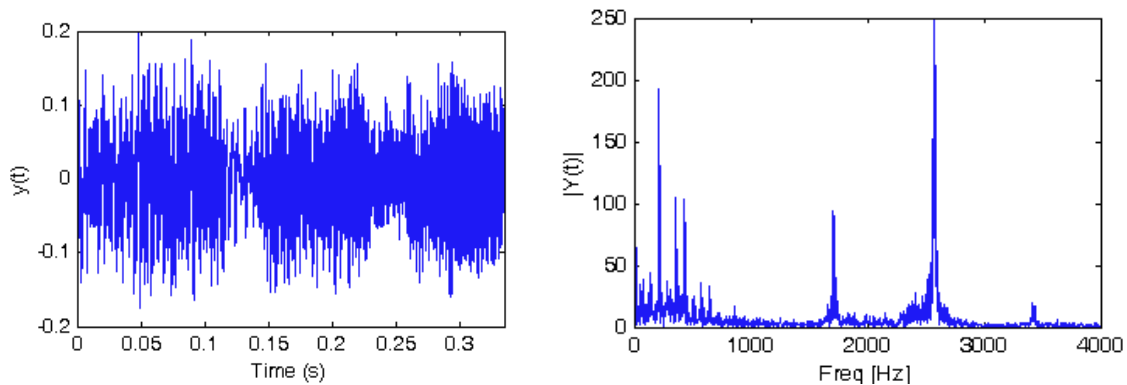


Figure 5: Beep audio cue. Graphs of warning cue properties show the beep cue as a 360 ms recording with 2 frequency peaks at 1700 Hz and 2500 Hz. The recording was looped to form a continuous warning cue for the LDWS used by Group 1.

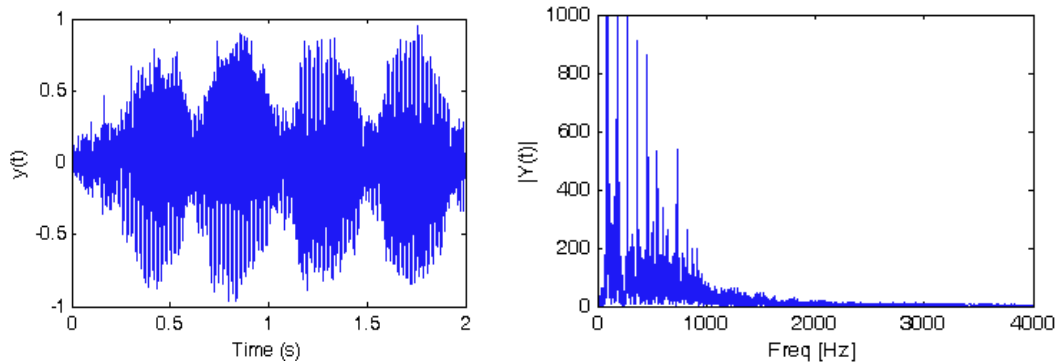


Figure 6: Rumble audio cue. Graphs of warning cue properties show the rumble cue as a 2 s recording, with 4 frequency peaks ranging from 90 -1000 Hz. The recording was looped to form a continuous warning cue for the LDWS used by Group 2.

	<i>No Cue</i>	<i>Beep</i>	<i>Rumble</i>
Rest	68 dB	78 dB	81 dB
30 km/h	75-82 dB	78-85 dB	82-83 dB
50 km/h	79-84 dB	80-84 dB	83-84 dB

Table 1: Audio cue decibel ranges. dB levels measured inside the simulator with the vehicle at rest, driving at 30km/h and 50 km/h. Ranges signify sound levels from closed to full throttle.

Design: Younger and older adults were equally divided into two experimental groups: beeps (Group 1) and rumble strips (Group 2) (Figure 7).

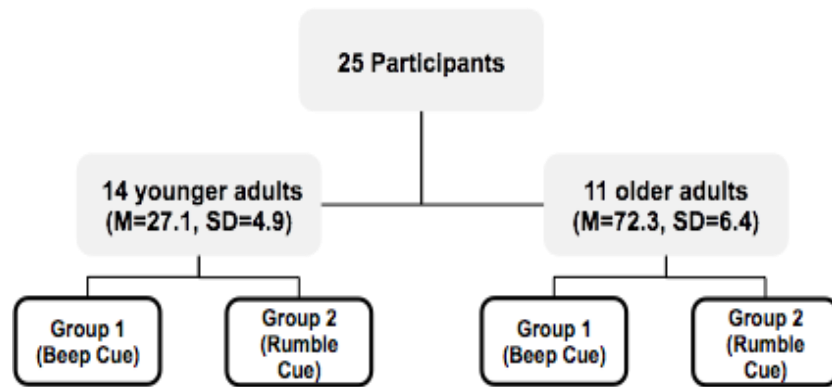


Figure 7: Experimental design overview. Figure indicates division of participants into two age groups and further into 2 designated audio cue LDWS groups.

A between subjects design was used to eliminate carryover effects between the two audio cueing conditions. The driving task was comprised of four ten-minute drives: 1) *Acclimatization Drive*: participants drove Course 1 in the simulator to gain familiarity with the system. The LDWS **was not** active in this phase. 2) *Baseline Drive*: participants drove Course 2 while driving performance measures were collected and used to establish baseline measures. The LDWS **was not** active in this phase. 3) *LDWS Drive*: from a varied starting position (across participants), each of the two groups drove Course 2 with their designated audio cue. The LDWS **was** active in this phase 4) *LDWS Intermittent Drive*: Participants returned to the baseline starting position and drove Course 2 a final time with their designated audio cue. In this phase LDWS **was** active, however, it was turned off intermittently (approximately every 500 m). Participants were not made aware of the intermittent “off” periods.

The starting positions within the driving environment were varied across the four drives to reduce the amount of repetition/learning effects due to familiarity with the environment and driving conditions. This created four possible course combinations (Table 2).

<i>Group</i>	<i>Warning Cue</i>	<i>Acclimatization</i>	<i>Baseline</i>	<i>LDWS</i>	<i>LDWS Intermittent</i>
Group 1-1	Beep	Course 1	Course 2, uphill	Course 2, downhill	Course 2, uphill
Group 1-2	Beep	Course 1	Course 2, downhill	Course 2, uphill	Course 2, downhill
Group 2-1	Rumble	Course 1	Course 2, uphill	Course 2, downhill	Course 2, uphill
Group 2-2	Rumble	Course 1	Course 2, downhill	Course 2, uphill	Course 2, downhill

Table 2 : Possible course combinations. All groups drove the same Course 1, then were divided into audio cue warning groups and further into staggered start position course combinations.

Throughout each of the drives, various measures were collected. A summary of dependent and independent measures is presented in Table 3 below. For further details of these measures, see section 4.1.

<i>Independent Variables</i>	
<i>Age</i>	Older vs. Younger
<i>Warning Cue</i>	Beep vs. Rumble
<i>Dependent Variables</i>	
<i>nDev</i>	Number of deviations (#)
<i>TimeDev</i>	Time of Deviations (s)
<i>MagDev</i>	Magnitude of Deviations (m)
<i>VelX</i>	Forward velocity (m/s)

Table 3 : Independent and dependent variables. Collected measures throughout each of the 4 drives.

Protocol: Following the completion of pre-testing measures, the driving task was thoroughly explained. Participants were accompanied by the study investigator in the simulator for the duration of the trial and instructions for each drive were reiterated prior to the start of each drive. Participants were briefed on the format of the four drives. Drive 1 was described as an acclimatization course where they would aim to drive maximum 80 km/h and stay within their starting lane for the duration. Drive 2 was described as a baseline course where they would aim to follow all speed signs indicating maximum 50 km/h on straighter stretches and maximum 30 km/h on hairpin curves, staying within their starting lane for the duration. Participants were told this course would not have the LDWS activated. Drive 3 and 4 were described exactly as Drive 2, however in these courses participants were told the LDWS would be activated. After completion of the entire driving task, participants were debriefed and requested to fill out the Driving Comfort Scales (Myers, Paradis, & Blanchard, 2008) (Appendix 2), the Internality/Externality Questionnaire (Montag & Comrey, 1987) (Appendix 3), and the Short Simulator Sickness Questionnaire (SSQ) (Kennedy, Lane, Kevin, & Lilienthal, 1993) (Appendix 4).

Simulator Sickness: Simulator sickness (SS) is a unique form of motion sickness experienced in simulators. Though causes and indicators for susceptibility are still being investigated, one possible explanation for this phenomenon is provided by the sensory conflict theory (Reason, 1978; Reason & Brand, 1975). This theory implies that feelings in the realm of nausea, pallor, sweating or vomiting, are caused by conflicting inputs from the various sensory modalities (e.g.

visual inputs that specify self-motion and body-based cues that indicate different or absent information specifying self-motion); typically the greater the conflict, the stronger the symptoms. While simulator sickness is relatively common, symptoms vary and are typically resolved quickly following removal of the stimulus or acclimatization.

For this study, every effort was made to reduce simulator sickness among participants. During participant screening, conservative cut-offs for the MSSQ-S scores were chosen to ensure participants did not have indication for high susceptibility to simulator sickness. Furthermore, participants were briefed on the signs and symptoms to look out for during the driving task. All precautions were taken to mitigate SS, including a gentle adaptation phase, keeping the simulator interior cool, proper ventilation, calibrated eye height, and breaks between drives. Throughout the simulation, the investigator used the Fast Motion Sickness Scale (FMS) (Appendix 5) to track symptoms of SS, asking the participant every minute for a numeric response on a scale of 0-20 (0 being perfectly fine, 20 being severe nausea) to represent their current feeling (Keshavarz & Hecht, 2011). The experiment was halted when responses were >10, or at any time the participant asked to stop and withdraw from the study. Following the driving task, participants completed the SSQ to gauge overall feelings of SS.

Chapter 4

4.1 Data Analysis

Throughout the simulation, data was recorded at a frequency of 100 Hz within the OKTAL SCANeRTM studio software. Measures of interest were exported and filtered through a MATLAB script, which calculated overall dependent measure scores and segmented data into segments and trigger sections for further analysis.

Several mixed factorial ANOVAs (ANOVA designs described in Section 4.2) were performed on each of the dependent measures. Between-subjects variables included: 1) age group; 2) warning cue. Within-subjects variables included: 1) drives (i.e. Baseline, LDSW, LDWS Intermittent). For some analyses, Course 2 was broken down into segments of road complexity (curve vs. straight) (Appendix 6) and trigger sections where the LDWS was intermittently turned off (ON vs. OFF) (Appendix 7), for direct comparison of road sections. Dependent measures for each analysis included:

- the sum (per participant, per drive) or average (per participant, per segments/triggers) number of deviations (**nDev**) (Figure 8);
- the average (per participant, per drive/segments/triggers) amount of time the vehicle deviated from the lane boundary, in seconds (**TimeDev**) (Figure 9);
- the average (per participant, per drive/segments/triggers) magnitude of deviations from the lane boundary, in meters (**MagDev**) (Figure 10);
- the average (per participant, per drive/segments/triggers) vehicle's velocity in the forward direction (**VelX**).

The RMS of deviations (**RMSDev**) and maximum point of deviations, from the lane boundary in meters (**MaxDev**), were also collected but showed trends which are equally represented by the **MagDev** measure, and thus, will not be reported here. While MaxDev is an additional measure of importance, it only provides a brief snapshot of the lane deviation at its most severe point; while MagDev indicates an average distance over the course of the whole deviation. In an effort to showcase the most representative distance of deviation on average, the more conservative measure of MagDev was selected for reporting here. Supplementary bivariate correlation analyses comparing FMS scores with dependent measures, and SSQ scores with dependent measures were conducted, which confirmed there were no significant effects of SS on participants' driving performance.

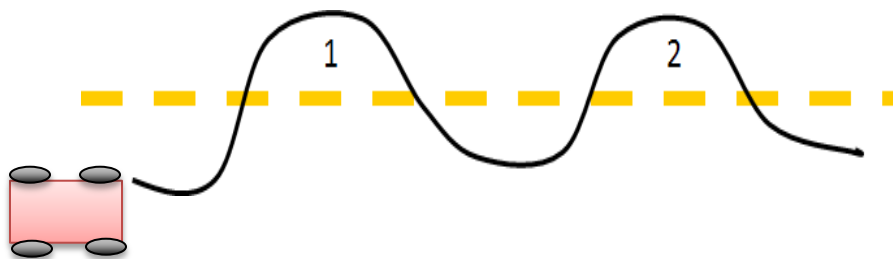


Figure 8: nDev dependent measure. nDev is the counted number of deviations from the left or right road lane boundary starting when the wheel crossed a lane boundary and ending when the wheel returned to fully within a lane boundary. In this example, nDev would equal 2.

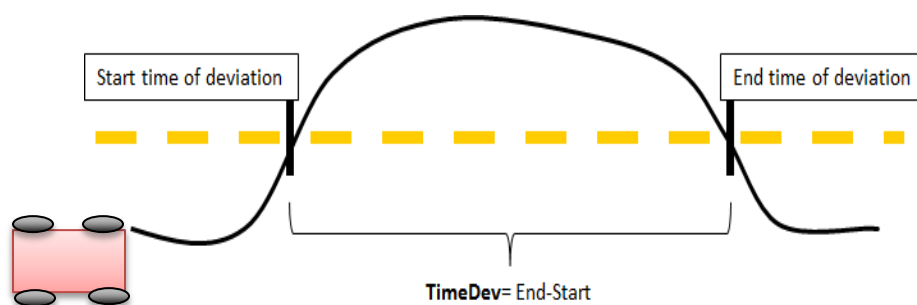


Figure 9: TimeDev dependent measure. TimeDev (s) calculated by subtracting the time point when a deviation started from the time point when a deviation ended. The time point at start of deviation was the time at which the wheel crossed a lane boundary and the time point at the end of deviation was the time at which the wheel returned to fully within a lane boundary.

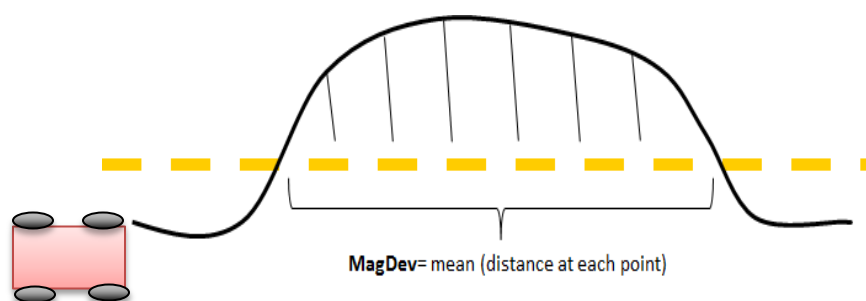


Figure 10: MagDev dependent measure. MagDev(m) calculated by taking the mean of the distance of the wheel from the lane boundary across all time points during one deviation event.

4.2 Results

An initial analysis confirmed no significant differences for any of the dependent measures at Baseline were observed between the two age groups or warning cue groups.

Effectiveness of Warning Cue: The first analysis compared driving performance in the Baseline Drive vs. LDWS Drive across all participants. A 2 (age: younger vs. older) x 2 (cue: beep vs. rumble) x 2 (Baseline drive vs. LDWS drive) mixed factorial ANOVA, was used to assess each

dependent measure. **nDev:** Results showed a significant main effect of driving with a warning system vs. without, such that driving with a LDWS resulted in fewer deviations ($M= 11.504$) compared to without ($M=26.096$), $F(1,21)=27.131$, $p < 0.001$ (Figure 11). No main effects of age or cue type, or interaction effects were observed. **TimeDev:** In comparison to the Baseline Drive ($M=0.162$ s), driving with LDWS ($M=0.122$ s) lead to a main effect of significantly reduced TimeDev ($F(1,21)=7.56$, $p < 0.05$). No other main effects of age or cue type, or interactions were found. **MagDev:** In addition, driving with LDWS also resulted in a main effect of significantly reduced MagDev ($M=1.208$ m) as compared to the Baseline drive without a warning system ($M=2.116$ m), ($F(1,21)=19.06$, $p < 0.001$). No main effects of age or cue type, or interaction effects were observed. **VelX:** No significant interactions were identified. This indicates that the introduction of an LDWS, regardless of drivers' age or warning cue type, resulted in fewer, shorter and smaller lane departures.

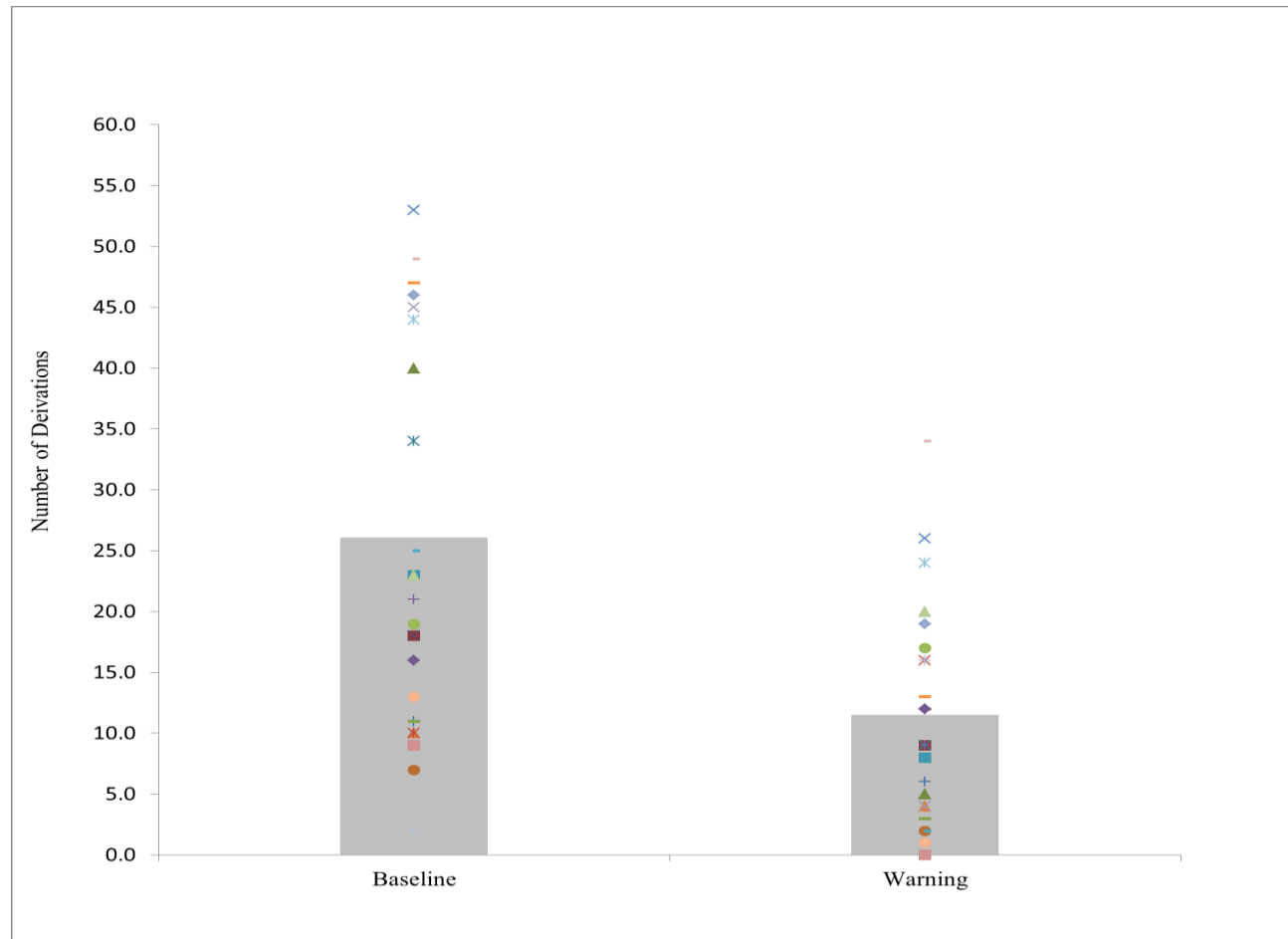


Figure 11: Main effect of LDWS in Baseline vs. LDWS drives. The average of the sum of deviations across all participants is shown in bar graphs. $F_{(1,21)}=27.131$, $p < 0.001$. Individual participant sum scores are plotted for both the Baseline and LDWS drive.

We also examined the influence of “experience” driving with a LDWS over the short time period for which it was available (i.e. across the 10 min LDWS drive). Thus, we separated the first two and last two segments of each participant’s LDWS drive and compared them using a 2 (age: younger vs. older) x 2 (cue: beep vs. rumble) x 2 (condition: 1st half of LDWS drive vs. 2nd half of LDWS drive) mixed factorial ANOVA. **nDev:** Results showed a main effect of significantly fewer deviations in the last portion of the drive ($M=1.34$) vs. the first ($M=0.8$), $F(1,21)= 5.37$, $p=0.03$. No other main effects regarding age or interactions were observed. **TimeDev:** No main effects of age, segment or warning cue were found. A warning cue-by-segment interaction showed that experience with the cues led to significantly shorter deviations with the beep cue (First segment $M=0.93s$, Last Segment $M=0.25s$) during the last segment, $F(1,21)= 4.53$, $p=0.045$, but not the rumble cue (First segment $M=0.95s$, Last Segment $M=1.05s$) (Figure 12). No other interactions were observed. **MagDev:** No main effects of age, segment or warning cue were observed. A warning cue-by-segment interaction showed experience with the rumble cue (First segment $M=0.08m$, Last Segment $M=0.12m$) led to significantly larger deviations in the last segment, $F(1,21)= 4.45$, $p=0.047$, while the beep cue showed no significant difference (First segment $M=0.08m$, Last Segment $M=0.03m$) (Figure 13). **VelX:** A significant main effect of age showed that overall, older adults ($M=30.8m/s$) drove significantly slower than the younger adult group ($M=34.5m/s$), $F(1,21)=4.55$, $p=0.045$ (Figure 14). No other main effects of warning cue or segment, or interactions were observed.

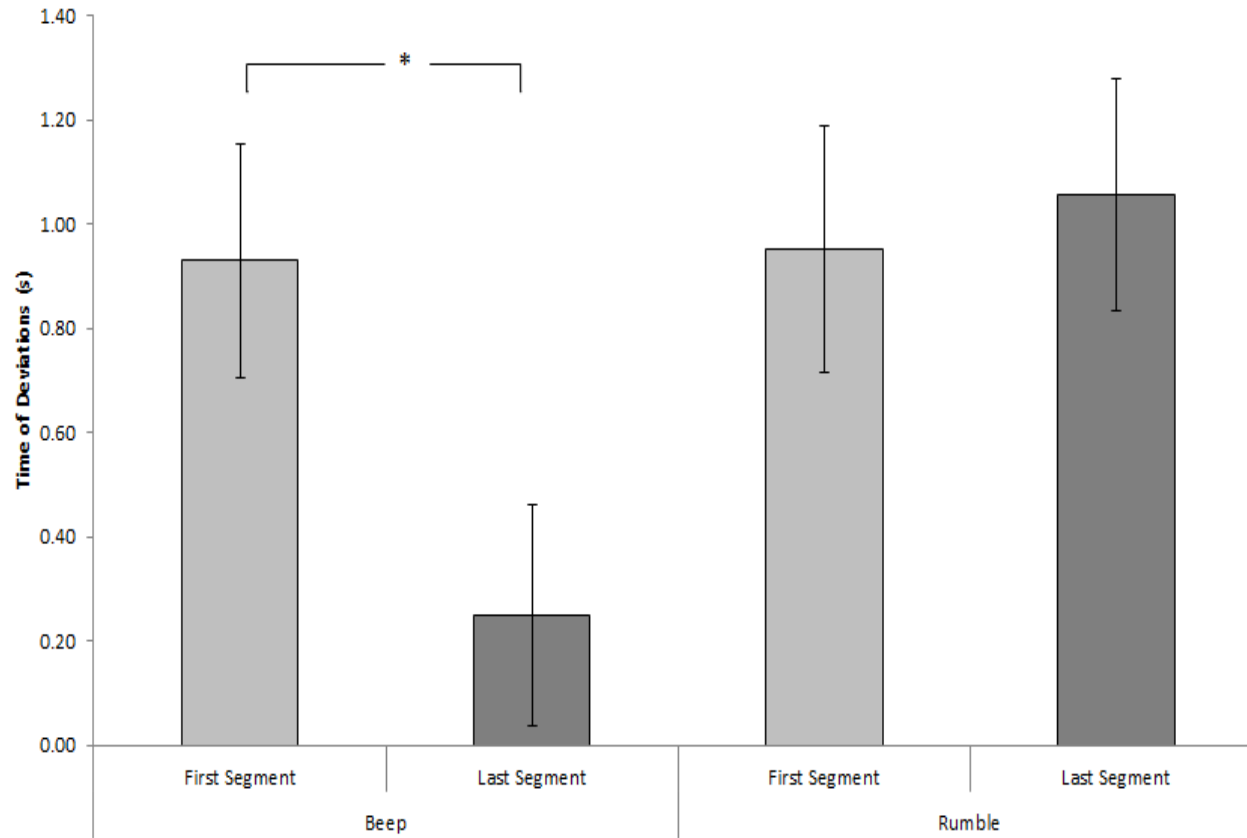


Figure 12: TimeDev warning cue-by-segment interaction. Exposure to the beep cue warning shows significantly less time of deviations in last segments of LDWS drive compared to first segments. $F_{(1,21)} = 4.53$, $p < 0.05$, error bars are $\pm 1SE$.

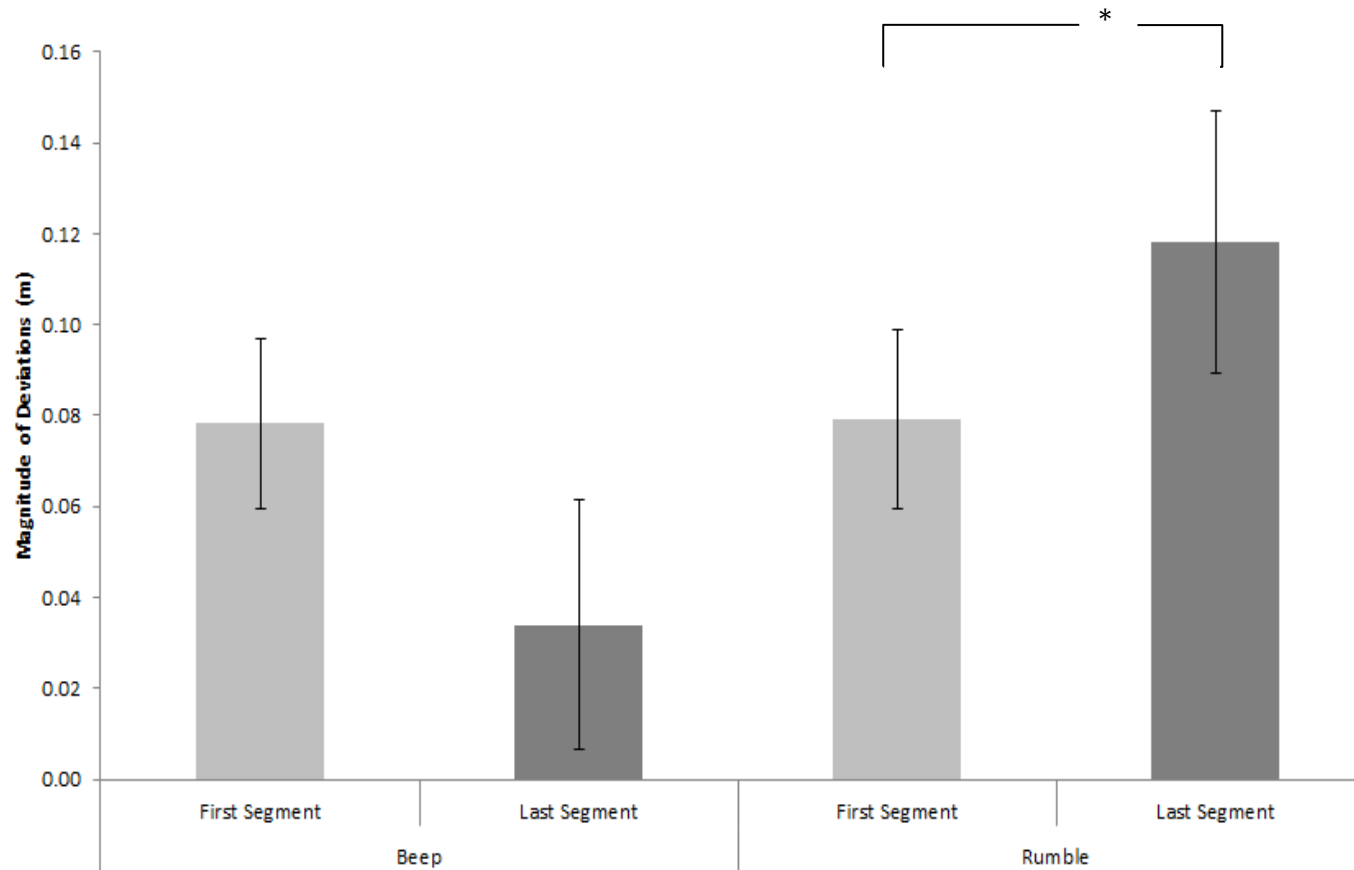


Figure 13: MagDev warning cue-by-segment interaction. Exposure to the rumble cue warning shows significantly larger deviations in the last segments of LDWS drive. $F_{(1,21)} = 4.45$, $p < 0.05$, error bars are $\pm 1SE$.

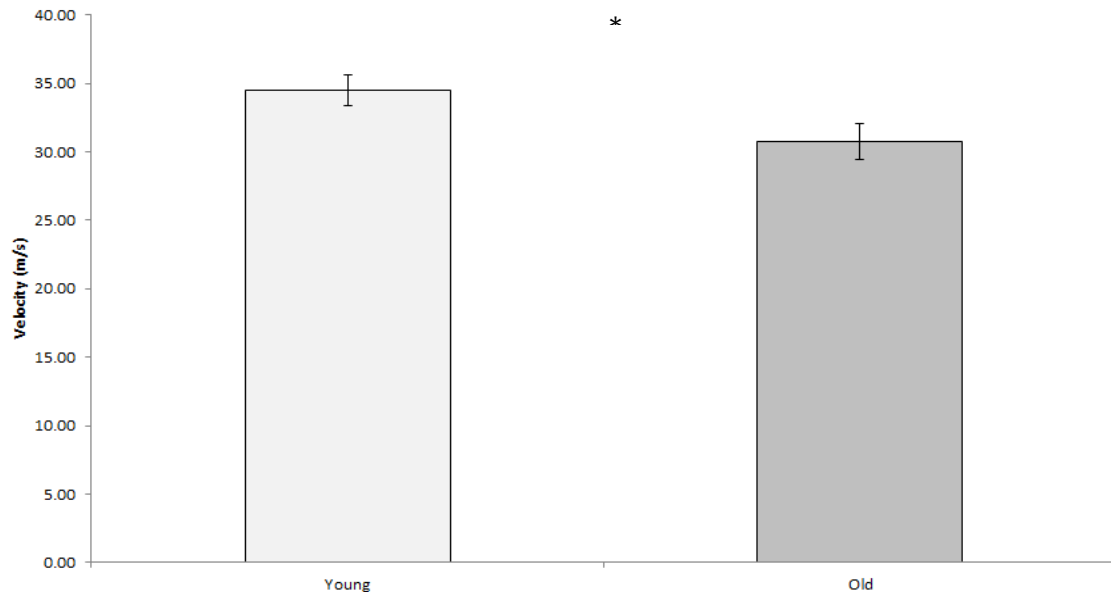


Figure 14: Main effect of VelX in Baseline vs. LDWS drive. Overall segment analysis shows older adults drove significantly slower than the younger adult group, $F_{(1,21)}=4.55$, $p<0.05$, error bars are $\pm 1SE$.

In order to address whether more complex/more curved segments of road revealed differences in lane keeping under different cueing conditions and/or between different age groups compared to less complex/straighter segments of road, a third analysis compared the means of all curved segments and all straighter segments in the Baseline and LDWS Drive. For this comparison, we used a 2 (age: younger vs. older) x 2 (cue: beep vs. rumble) x 2 (complexity: straights vs. curve) x 2 (drive: Baseline vs. LDWS) mixed factorial ANOVA. **nDev:** Results showed a significant main effect of road complexity with significantly more nDev on the straighter segments ($M=2.31$) compared to curved segments ($M=1.24$), $F(1,21)=35.69$, $p<0.001$. An age-by-complexity interaction showed older drivers showed significantly more nDev in straighter segments ($M=2.95$) than and younger drivers on straighter segments ($M=1.67$), $F(1,21)=8.970$, $p<0.01$. A complexity-by-drive interaction showed significantly more nDev in the straighter

segments of the Baseline drive ($M=3.27$) compared to the straighter segments of the LDWS drive ($M=1.35$), and significantly more nDev in the curves of the Baseline drive ($M=1.65$) compared to the curves of the LDWS drive ($M=0.83$), $F(1,21)=12.697$, $p<0.01$ (Figure 15).

TimeDev: A main effect of complexity shows, significantly longer deviations in curved segments ($M=1.49$ s) compared to straight segments ($M=1.21$ s), $F(1,21)=7.269$, $p=0.01$. A complexity-by-drive interaction revealed significantly longer TimeDev on curves of the Baseline drive ($M=2.26$ s) compared to the straights in the Baseline drive ($M=1.76$ s), $F(1,21)=5.05$, $p<0.04$, but with an LDWS active, no such difference was observed (Figure 16). A marginally significant 4-way interaction indicated older drivers had shorter TimeDev on the curves of the LDWS drive compared to the curves of the Baseline drive with both the beep (Baseline $M=1.8$ s, LDWS $M=0.5$ s) and the rumble (Baseline $M=3.1$ s, LDWS $M=1.1$ s), $F(1,21)=4.228$, $p=0.052$.

MagDev: No significant main effects or interaction were observed regarding course complexity.

VelX: A main effect of complexity shows participants drove significantly faster in the straighter segments ($M=40.4$ m/s) compared to the curved segments ($M=30.6$ m/s), $F(1,21)=232.754$, $p<0.001$. No other significant main effects or interactions were identified.

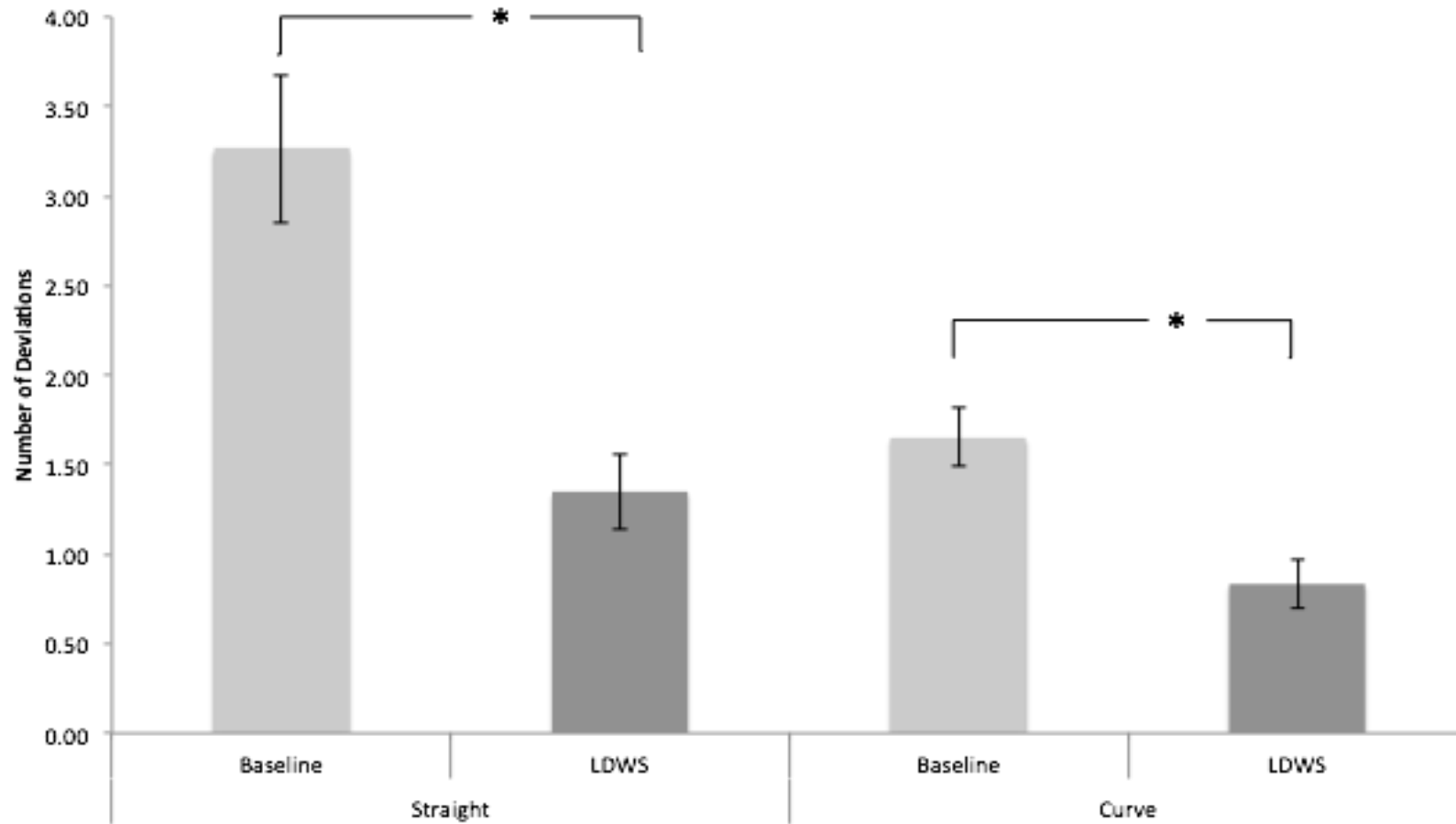


Figure 15: nDev complexity-by-drive interaction. Graph shows significantly more deviations in curves and straighter segments in the Baseline drive compared to the LDWS drive, $F_{(1,21)}=12.697, p<0.01$, error bars are $\pm 1SE$.

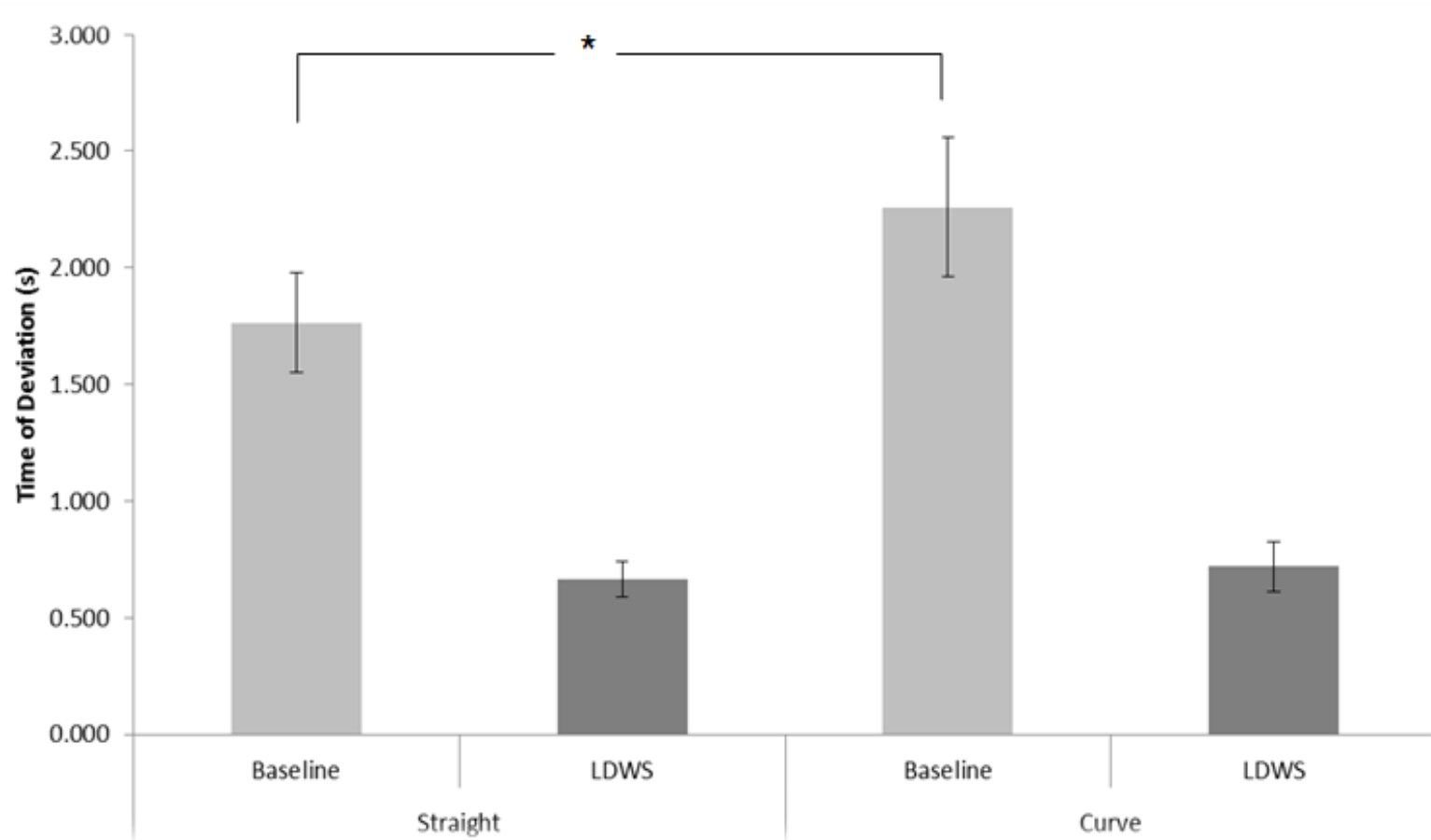


Figure 16: TimeDev complexity-by-drive interaction. Graph shows that deviation times are significantly longer on curves in the Baseline drive, but this difference does not exist when the warning system is active. $F_{(1,21)} = 5.05$, $p < 0.05$, error bars are $\pm 1SE$.

Behavioural Adaptation:

Two analyses were conducted to observe adaptation effects: 1) comparing the ON sections of the LDWS drive vs. the OFF sections of the LDWS Intermittent drive (ON vs. OFF Between), 2) comparing the ON vs. OFF sections within the LDWS Intermittent drive (ON vs. OFF Within). Graphs for both analyses have been clustered by dependent measure.

In order to compare across the exact same segments of road (i.e. same road conditions, road geometry, environmental cues) it was necessary to compare the OFF sections of the LDWS Intermittent drive (drive 4) with the IDENTICAL sections of road in the LDWS drive (drive 3). To analyze possible effects of short-term adaptation, sections of the *LDWS Intermittent* drive (drive 4) where the system was OFF were compared with the identical sections in the *LDWS drive* (drive 3) where the system was constantly ON. To make this comparison, a 2 (age: younger vs. older) x 2 (cue: beep vs. rumble) x 2 (segment: ON segments of LDWS drive vs. OFF segments of LDWS Intermittent drive) mixed factorial ANOVA was conducted. **nDev:** A main effect showed significantly more deviations in the sections where the LDWS was ON ($M=0.99$) compared to the same road sections when it was OFF ($M=0.56$), $F(1,21)=8.86$, $p=0.007$ (Figure 17). A main effect of warning cue, in the LDWS Drive and LDWS Intermittent drives showed significantly more deviations with the rumble cue ($M=1.01$), $F(1,21)=4.330$, $p=0.05$, compared to the beep cue ($M=0.54$) (Figure 18). No main effects of age, or other interactions were identified. **TimeDev:** A main effect of warning cue shows overall, there were longer deviations with the rumble cue ($M=1.13s$) than the beep cue ($M=0.65s$), $F(1,21)=7.55$, $p<0.05$ (Figure 19). No other main effects of age, or LDWS ON vs. OFF were observed. An age-by-ONvsOFF

interaction showed older drivers exhibited marginally significantly longer deviations, $F(1,21)=4.25$, $p=0.052$, in the OFF condition ($M=1.15s$) compared to when it was ON ($M=0.66s$), while younger adults displayed no such change in performance (Figure 20). No other interactions were significant. **MagDev**: No significant main effects or interactions were observed. **VelX**: No significant main effects or interactions were found regarding velocity.

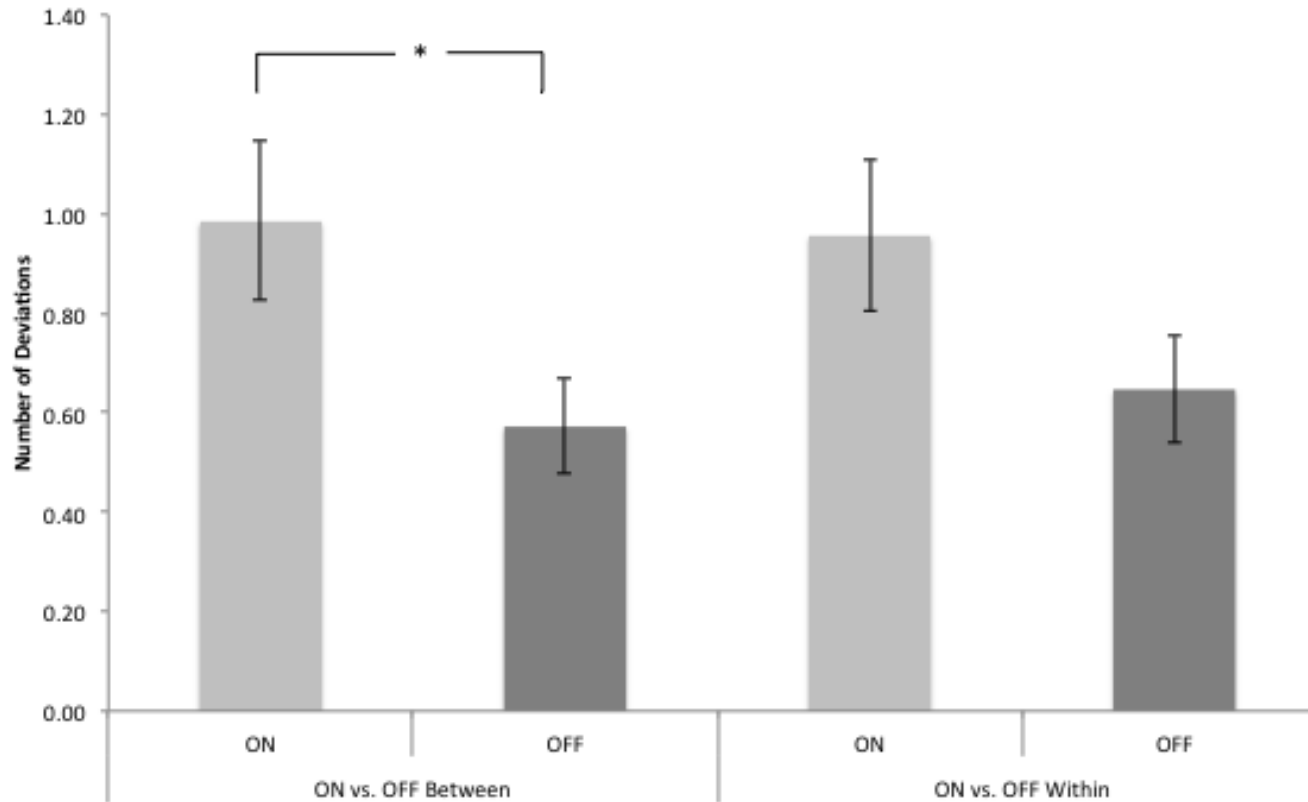


Figure 17: nDev main effect of ON vs. OFF. Graph shows significantly more deviations in the ON sections of the LDWS drive compared to the OFF sections of the LDWS Intermittent drive ($F_{(1,21)}=8.86$, $p<0.01$), and approaching significantly more in the ON sections vs. the OFF sections within the LDWS Intermittent drive ($F_{(1,21)}=3.949$, $p=0.060$). Error bars are $\pm 1SE$.

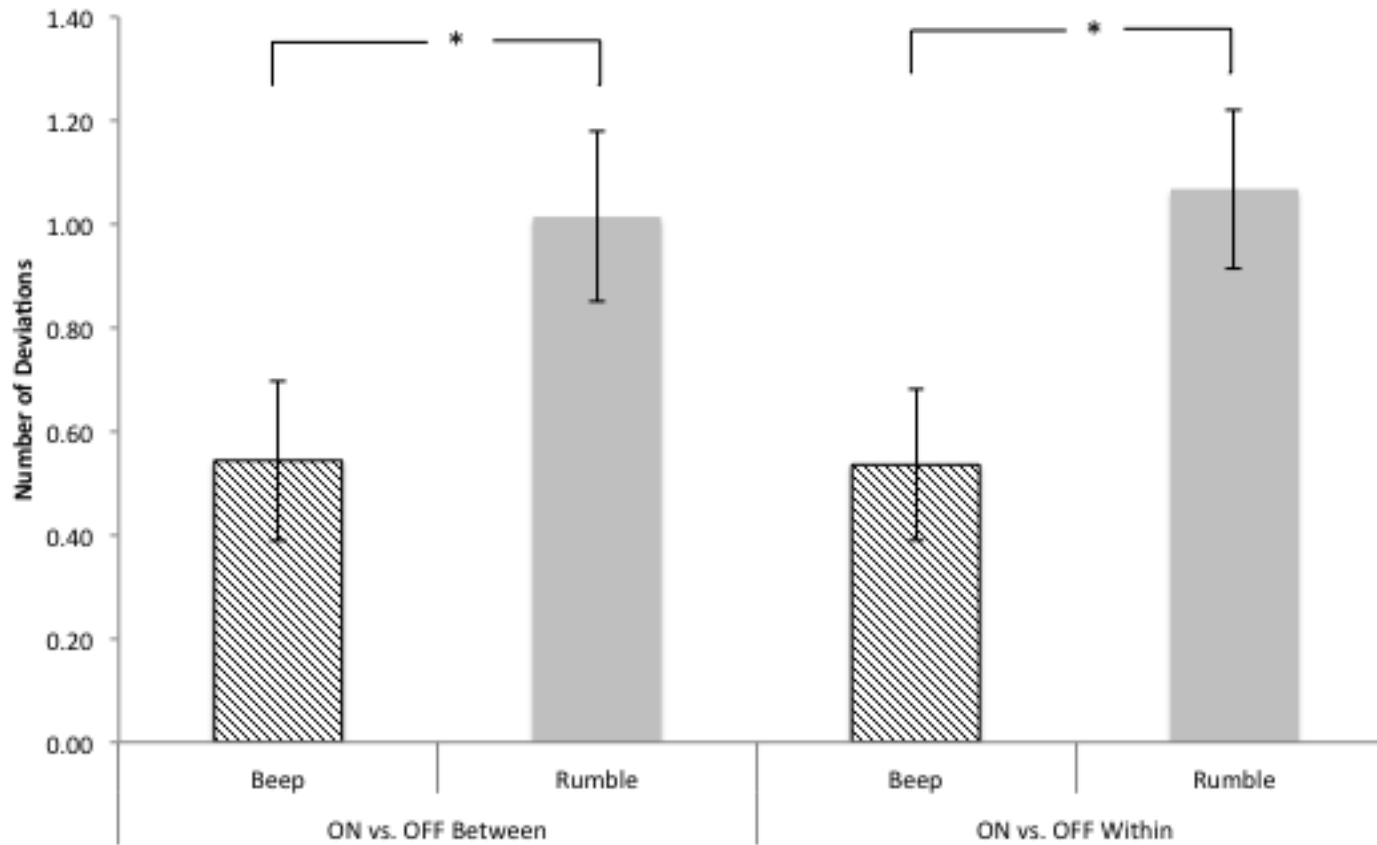


Figure 18: nDev main effect of warning cue in ON vs. OFF. Graph shows mean number of deviations by audio cue group between ON sections of LDWS drive compared to OFF sections of LDWS Intermittent drive ($F_{(1,21)} = 4,330, p = 0.05$), and ON vs. OFF sections within the LDWS Intermittent drive ($F_{(1,21)} = 6.31, p < 0.05$). Error bars are $\pm 1SE$.

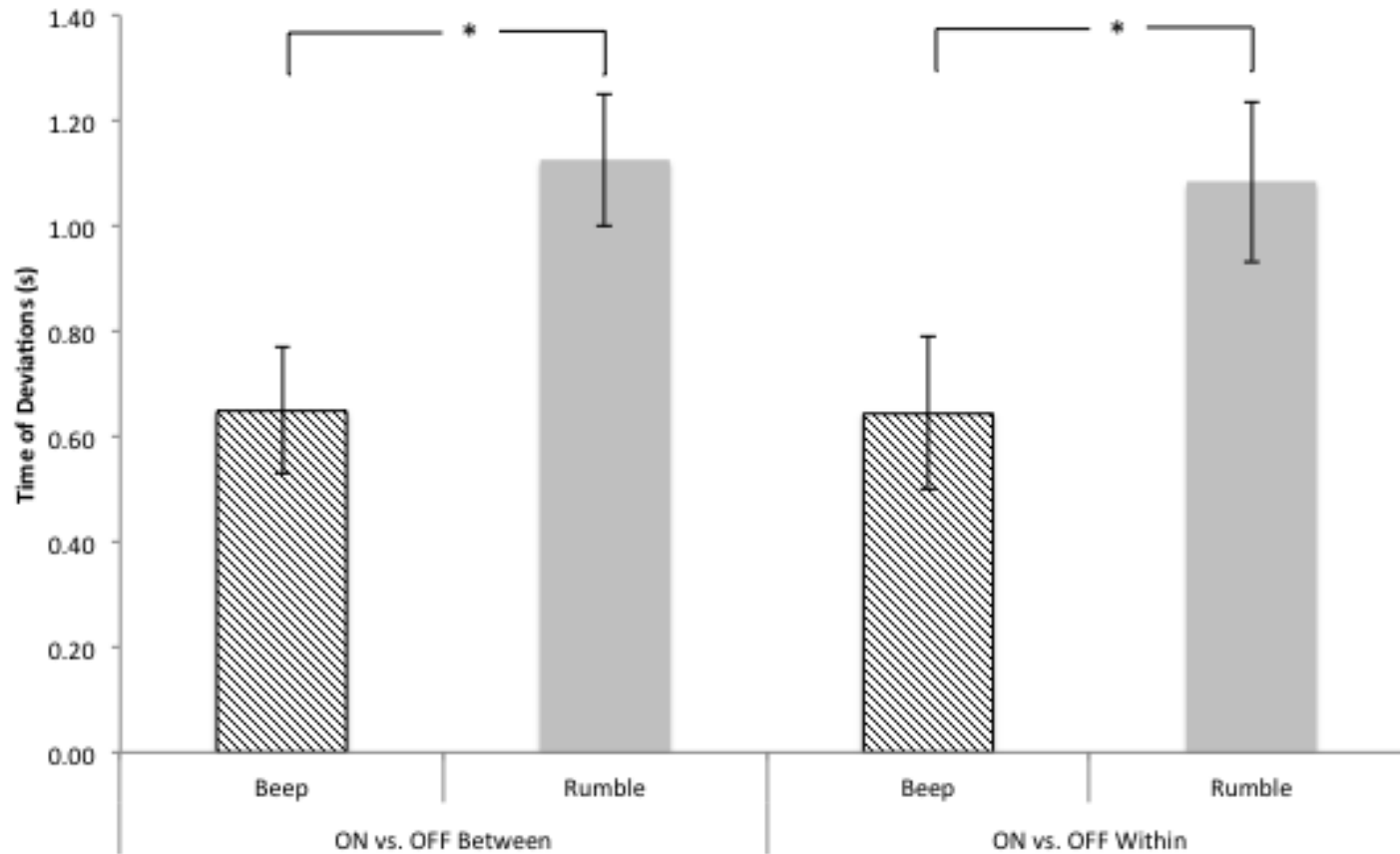


Figure 19: TimeDev main effect of warning cue in ON vs. OFF. Graph shows mean time of deviations by audio cue group between ON sections of LDWS drive compared to OFF sections of LDWS Intermittent drive ($F_{(1,21)}=7.55, p<0.05$), and ON vs. OFF sections within the LDWS Intermittent drive ($F_{(1,21)}=4.37, p<0.05$). Error bars are $\pm 1SE$.

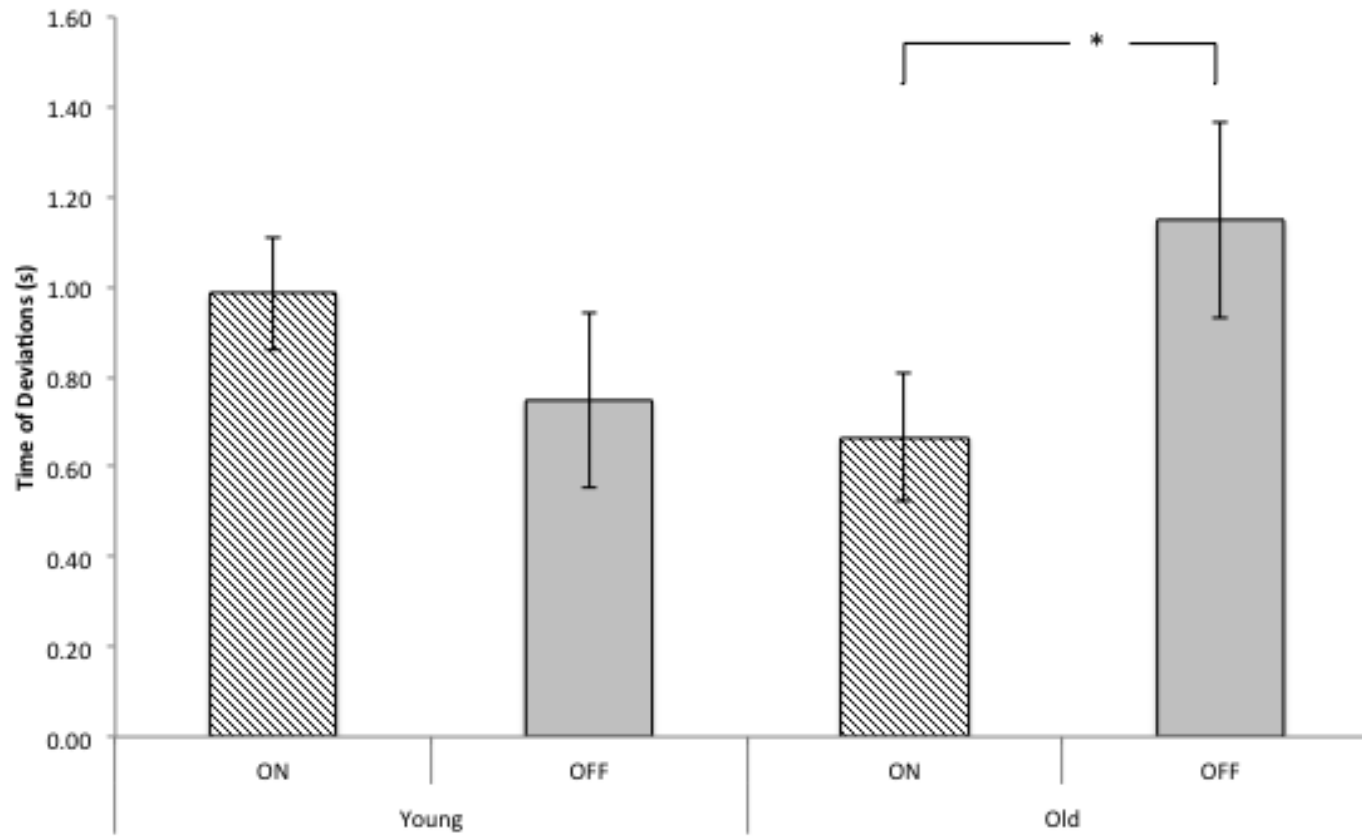


Figure 20: TimeDev age-by-ONvsOFF interaction. Graph shows mean time of deviations by age group in ON sections of LDWS drive vs. OFF sections of LDWS Intermittent drive. Results indicate significantly longer deviations in the OFF sections in the older age group. $F_{(1,21)} = 4.25$, $p = 0.052$, error bars are $\pm 1SE$.

Although by comparing identical road sections in drives 3 and 4 allowed for the most comparable analysis in terms of driving conditions, it is also confounded by potential practice effects. Therefore, a further analysis was conducted comparing the OFF and ON segments exclusively within the LDWS Intermittent drive (i.e. all contained within drive 4). A 2 (age: younger vs. older) x 2 (cue: beep vs. rumble) x 2 (segment: ON segments of LDWS intermittent drive vs. OFF segments of LDWS intermittent drive) mixed factorial ANOVA was run to assess these effects. **nDev:** A main effect approaching significance shows that when comparing ON and OFF sections within the same drive, there were more deviations in the segments where the LDWS is ON ($M=0.96$), compared to when it was OFF ($M=0.65$), $F(1,21)=3.949$, $p=0.060$ (Figure 17). A main effect of age shows there are significantly more deviations in older adults ($M=1.11$) compared to younger adults ($M=0.49$), $F(1,21)=8.60$, $p<0.01$. A main effect of warning cue exhibits more deviations with the rumble cue ($M=1.07$) compared to the beep cue ($M=0.54$), $F(1,21)=6.31$, $p=0.02$ (Figure 18). There were no interactions found with regards to nDev. **TimeDev:** There were no significant main effects between ON and OFF sections or age with regards to TimeDev. A main effect of warning cue shows significantly longer deviations with the rumble cue ($M=1.08s$) compared to the beep cue ($M=0.64s$), $F(1,21)=4.37$, $p=0.049$ (Figure 19). No interactions were significant. **MagDev:** No significant main effects of ON vs. OFF sections, age, or warning cue were identified. A warning cue-by-ON vs. OFF interaction showed marginally significant larger deviations in the ON sections with the rumble cue ($M=0.13m$) compared to the OFF sections with the rumble cue ($M=0.08m$), $F(1,21)=4.22$, $p=0.053$ (Figure 21). **VelX:** A review of velocity shows a main effect where all participants

drove significantly faster in the OFF sections ($M=42.5$ m/s), compared to the ON sections ($M=39.7$ m/s), $F(1,21)=11.010$, $p=0.003$.

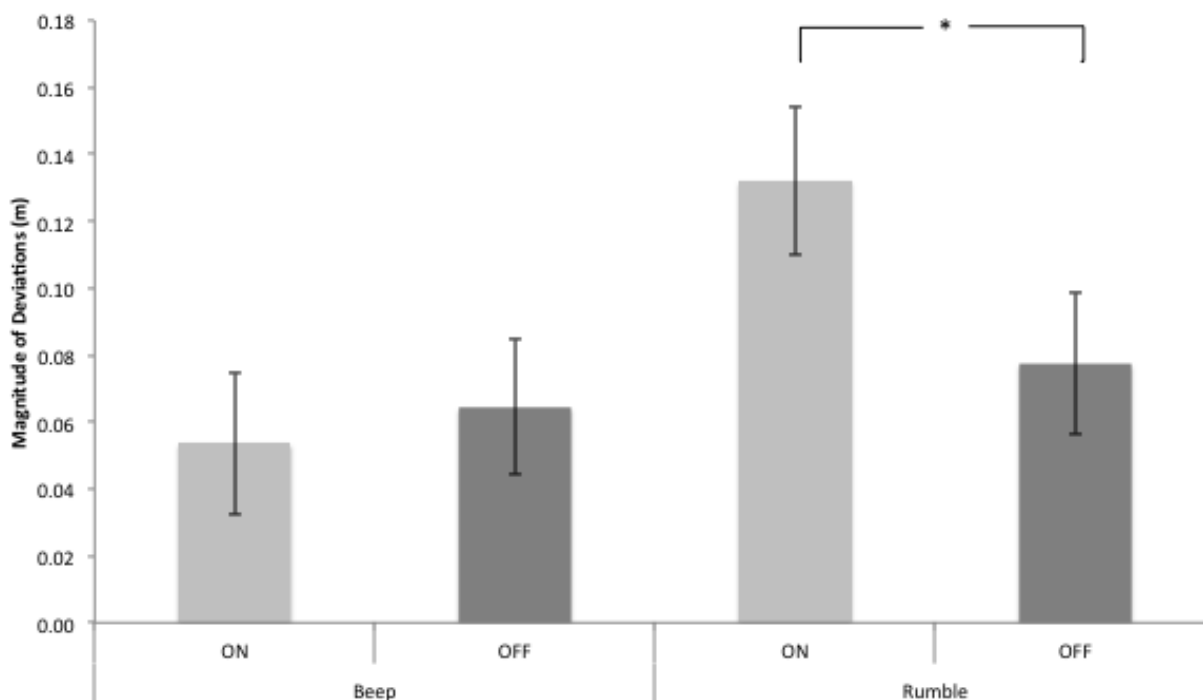


Figure 21: MagDev warning cue-by-ONvsOFF interaction. Graph shows magnitude of deviations by warning cue in ON vs. OFF sections within the LDWS Intermittent drive. Results indicate significantly larger deviations in the ON segments compared to the off segments with the rumble cue, $F_{(1,21)}=4.22$, $p=0.053$, error bars are $\pm 1SE$.

In the interpretation of the analyses described above it was important to consider whether participants did, in fact, deviate from their lane during the LDWS drive and LDWS Intermittent drive. Without satisfying these criteria, it would be difficult to identify whether a) having a warning system active would have any effect or b) that turning off the warning system would have any effect. Therefore, in order to ensure this criteria was met for each drive, we plotted

number of deviations, per participant, per drive to observe deviation behaviours. While 2 participants in the ON in LDWS drive vs. OFF in LDWS Intermittent drive and 4 participants in the ON vs. OFF within LDWS Intermittent group showed zero deviations in both the ON and OFF sections, their data was not excluded from the current analysis. Even in taking the conservative approach by including all participant data in these analyses, the results are significant, thus the overall effect of LDWS is likely strong. By removing the participants who showed zero deviations in the specific ON/OFF segments from the analyses, additional and/or stronger effects may be shown in future analyses.

A supplemental analysis was run to address the possibility of learning effects associated with greater practice driving in the simulator across consecutive drives (in other words, was the improvement in driving in the LDWS condition related to the cueing system itself or simply due to practice with the simulation). In order to assess this, the last segments (1 curve, 1 straight: app. 1km) from the end of the baseline drive were compared with starting segments (1 curve, 1 straight: app. 1km) of the LDWS drive, and the last segments (1 curve, 1 straight: app. 1km) from the end of the LDWS drive were compared with starting segments (1 curve, 1 straight: app. 1km) of the LDWS Intermittent drive. These segments occurred in direct succession of one another, thus the amount of “practice” should be roughly equal during these segments. Two 2 (age: younger vs. older) x 2(segment: end of 1 vs. start of 2) and 2 (age: younger vs. older) x 2(segment: end of 2 vs. start of 3) mixed factorial ANOVAs were run for each dependent measure. (See Practice Effects 1 below, and Practice Effects 2 in later results).

Practice Effects 1 (End of 1, Start of 2): It was predicted that any practice effects would lead to less number of deviations, shorter deviations and/or smaller deviations for later segments compared to earlier segments. **nDev:** Results showed no significant difference in nDev between the End of 1 and the Start of 2. Additionally, no significant main effects of age or interactions were found. **TimeDev:** Deviations in the End of 1 were significantly longer ($M=1.7$ s) than Start of 2 ($M=0.9$ s), TimeDev ($F(1,23)=10.18$ $p=0.004$). No significant main effects of age or interactions were found. **MagDev:** Deviations in the End of 1 ($M=0.14$ m) were significantly larger than Start of 2 ($M=0.8$ m), ($F(1,23)=6.68$, $p=0.017$). No significant main effects of age or interactions were found. **VelX:** There were no significant main effects or interactions regarding VelX. These results indicate practice effects may play a role in the first set of analyses comparing the Baseline drive to LDWS drive, therefore, possibly showing inflated effectiveness of the LDWS system on lane keeping performance.

Practice Effects 2 (End of 2, Start of 3): Results show no significant difference in nDev, TimeDev, MagDev, or VelX between segments. Implications from this analysis suggest adaptation effects seen in the previous results section are not merely a product of practice effects.

Chapter 5

5.1 Discussion

5.1.1 LDWS Effectiveness

Overall Effectiveness of LDWS (Baseline vs. LDWS Drive): Results of this study demonstrated that upon first exposure to a Lane Departure Warning System (LDWS), using either the icon or earcon, drivers' lane keeping performance was dramatically improved. Specifically in line with our first hypothesis that LDWS would lead to better lane keeping than driving without a warning system, participants made significantly fewer, shorter, and smaller deviations when exposed to LDWS compared to the Baseline drive. These findings are therefore consistent with previous results showing that LDWS, regardless of the audio cue type tested, leads to better lane keeping performance than no system at all (Fung et al., 2007; Rossmeier et al., 2005). Contrary to initial predictions, when comparing the full Baseline drive with the LDWS drive, the results showed no main or interaction effects associated with warning cue type and age. In this, we see that introduction of a LDWS is effective in increasing drivers' lane keeping behaviour (number, time, and magnitude of deviation) compared to the Baseline drive, and the effectiveness is not mediated by age or audio cue warning type. However, this broad comparison of the total Baseline and LDWS drives may have washed out more subtle effects as it collapsed performance across time and different road types/complexities. Therefore, further analyses were conducted to look at the effects of course complexity and effectiveness of LDWS over a short period of time.

Course Complexity (Baseline vs. LDWS Drive): High number of deviations both with and without LDWS were seen throughout the experimental drives in this study. It must be noted that these numbers are much higher than what would be expected in a real life driving scenario and may be due to factors including difficulty level of the driving task and difficulty with lane keeping in a simulation environment. With regards to course complexity, in considering these results we must note the specifics of the experimental course design- while defined as “straighter” relative to the hairpin “curve” segments, the straighter sections of road were long and quite complex road structures with curves throughout (See Appendix 6). Results of road complexity showed for both age groups a greater number of deviations on straighter segments of road compared to curved segments, in both the Baseline and LDWS drives. The high number of deviations seen on the straighter segments of road may be attributable to the difficulty of the course and the more monotonous nature of the straighter road stretches, which compared to the curved segments, may have required less immediate conscious attention throughout the driving task. On these long stretches, drivers may have become slightly less attentive to their lateral position and thus, deviated from the lane boundary more frequently than on the curves. In addition, results showed participants drove significantly faster on the straighter sections of road, compared to the curved sections. Faster driving speeds have been associated with low-demand driving situations, supporting the proposed notion that driving on the straighter segments may have been less mentally taxing compared to the curved road sections (Metz, Schömig, & Krüger, 2011) and therefore participants may have felt less of a need to attend to their lane keeping. Moreover, the faster velocity in straighter segments may have contributed to more deviations as a higher

driving speed on such a complex course design may have led to less control in lateral position of the vehicle on the road.

While the above results imply worse performance on straighter segments in terms of number of deviations, additional measures reveal straighter segments did not show worse performance in all respects. A main effect of road complexity showed, overall, significantly longer deviation times in the curved segments of road compared to the straighter segments. Curves are a notoriously challenging portion of driving, often prompting drivers to slow down and devote attention to controlling vehicle trajectory (Godthelp, 1986). As seen in Rudin-Brown et al. (2014), increasing road complexity leads to increased mental workload for the driver. Considering the increased attention and mental workload required to drive on a curve, drivers may have been more preoccupied with not losing control of the car on the curve than giving sufficient attention to lane keeping- resulting in longer deviation times compared to the less mentally taxing, straighter road segments. Additionally, results showed deviations were significantly longer in the curves of the Baseline drive compared to the straighter segments of the Baseline drive, but with LDWS, a difference in time of deviation between the curves and straighter segments was negated. As with the above interpretation, the LDWS may have taken over the role of monitoring lateral movement in curved road sections, allowing the driver to better focus on the complex task of controlling the vehicle on the curve and alerting them to quickly readjust if deviation occurred. This quick readjustment would have been faster than seen without LDWS as it would have taken the driver more time to realize they were deviating in the first place, due to their primary focus being on controlling the car throughout the curve. This finding was more prominent in older drivers as results showed they had significantly shorter deviations on curve segments with

LDWS active, compared to the curved segments of the Baseline drive. Considering the cognitive, sensory and perceptual deficits that often accompany ageing (reviewed in Baldwin, 2002), the already challenging task of driving on curves may become even more difficult with age. As such, the LDWS may have been particularly helpful in assisting the older drivers by compensating for deficits and alerting drivers to react quickly to the warning if they began to deviate.

The above interpretation of findings can be concluded as follows: overall, with regards to LDWS effectiveness, results showed significantly fewer and shorter deviations in both curved and straighter segments when drivers were using LDWS compared to the Baseline drive. This echoes what was seen in the initial analysis, in that, when first introduced, an LDWS system was effective in improving the frequency and time of deviations. No significant effect of warning cue regarding road complexity was found, suggesting regardless of audio cue type, compared to the Baseline drive, LDWS was effective in reducing drivers' frequency and time of deviations. An interaction of age and road complexity revealed older drivers may benefit more than younger drivers from using LDWS to reduce their time of deviation on curved segments of road.

Effectiveness of Experience with a LDWS Over a Short Period of Time (Within LDWS drive):

Our results indicate that with fairly short exposure to the novel LDWS system (10 min) there were significantly fewer deviations in the last segments of LDWS drive (last 1km), compared to the first segments of the LDWS drive (first 1km). With regards to type of audio cue effectiveness in the LDWS drive alone, an overall main effect showed that the rumble cue lead to a

significantly greater number of deviations than the beep cue in both the first and last segments of the LDWS drive.

A possible explanation for greater effectiveness with the beep cue, overall, may be the superior ease of detectability and discrimination from driving environment sounds. The hypothesized benefit of the rumble cue being a meaningful sound without need for training may have been overshadowed by factors such as its monotonous nature, possible masking by other driving sounds, and/or lack of conveyed urgency. Bellotti et al. (2002), suggested that discontinuous sound may be easier to detect and locate than a continuous sound. While loudness of the cues was within a comparable decibel range, the rumble cue was comprised of a longer loop section with lower frequency (2s, 90Hz-1000Hz) than the beep cue (360ms, 1700Hz-2500Hz). In succession, the rumble cue looped formed a more monotonous, continuous sound. In comparison, the beep cue featured a short loop section which, when compiled, formed a stochastic, discontinuous cue. In conjunction, the rumble cue may not have been as effective as the beep cue due to its risk of blending with similar natural driving environment sounds (Mckeown et al., 2010). While the rumble cue was clearly audible over other simulated driving sounds, the naturalistic quality may have led to the cue being easily overlooked or ignored, particularly with extended exposure. This is supported through our results which show the beep cue as more effective than the rumble cue at reducing time and magnitude of deviations in the last section of the drive compared to the first.

Results also showed a driver's ability to react accordingly to a cue differed depending on the cue they received. While the beep cue lead to shorter deviations in the last sections of the LDWS

drive, trends (not significant) in the rumble cue showed slightly longer deviations in the last sections (First segment $M=0.95s$, Last Segment $M=1.05s$). Similarly, while the beep cue showed trends (not significant) toward smaller deviations between the first and last segments of the LDWS drive (First segment $M=0.08m$, Last Segment $M=0.03m$), the rumble cue showed significantly larger deviations in the last segments of the LDWS drive. The beep cue may have shown increasing effectiveness in reducing time of deviations due to a combination of its superior detectability and implied urgency with a short time of practice. Ben-Yaacov, Matlz, & Shinar (2002) showed with even short exposure to an audio beep warning system, drivers' headway performance improved with system use. As seen with their experiment, short-term use of the beep cue may have lead to improved cue reaction and therefore faster reaction upon hearing the cue, resulting in shorter deviations and slightly smaller deviations. Contrarily, the rumble cue may have shown decreasing effectiveness with exposure due to the aforementioned possible masking with environmental sounds and/or lack of conveyed urgency. Over time, the rumble cue may have become easier to ignore, prompting a more relaxed response to the cue compared to the beep cue. This likely accounts for the current study's findings of slightly longer deviations and significantly larger deviations with a rumble cue in the last sections of the LDWS drive compared to the first section of the drive.

While the current study's results appear to show better lane keeping performance with a beep cue sound, compared to the rumble cue, generalization of these effects over longer exposure times may vary. While the results presented in this thesis do not show support for inappropriate motor action in response to the cue, other work has shown startling cues may lead to consequential over-correcting (Edworthy, 1994). Furthermore, the beep cue may be more likely to lead to

annoyance, leading drivers to ignore their system or deactivate it completely, negating any positive effects which may be gained from having a LDWS. Moreover, the types of habituation that may have been observed for the rumble cue within the short timespan studied here, may also occur with a beep cue over more extended periods of exposure. Future work should consider the effects of more prolonged use of each system. Factors such as these must be considered when questioning the impact of our observed results regarding audio cue effectiveness.

Overall, our hypotheses regarding LDWS use were supported in our results demonstrating fewer deviations when the LDWS system was first introduced to drivers. Contrary to our initial hypothesis, the rumble cue appeared to show worse lane keeping performance than the beep cue, in terms of number of deviations overall, and increasingly worse performance with its use (significantly larger deviations and trend towards longer deviations in last segments). No evidence for difference among audio cue effectiveness in age groups was identified.

5.1.2 Behavioural Adaptation

In comparing both the ON sections of the LDWS drive to the OFF sections of the LDWS Intermittent drive, and the ON and OFF sections exclusively within the LDWS Intermittent drive, results surprisingly identified more deviations in segments of the road where the LDWS was ON, regardless of audio type. The initial hypothesis of this study was based on the theory that with greater exposure to a reliable system in the LDWS drive, drivers would become more comfortable with the system and show better lane keeping ability. Subsequently in the following drive where the system intermittently shut off, we expected to see *worse* lane keeping performance in the sections where the system was OFF. However, contradictorily to this

hypothesis, the current results suggest that LDWS did not lead to negative effects after the system was removed, but rather subconscious short-term adaptation effects were prompted by the use of LDWS, leading to more deviations with the system ON compared to OFF.

A possible explanation for finding more deviations in ON sections may include Näätänen & Summala's theory (1974) (see section 1.3.1), where advanced driver assistance systems hypothetically have the potential to increase a driver's accepted-risk level through increased risk exposure and resulting behavioural changes. When first introduced, LDWS was comparatively effective at reducing a driver's number of deviations; the warning alerts the driver to the perceived high-risk event of deviating from the lane so more care was taken to not deviate. This echoed LeBlanc's work where they reported initial exposure to a LDWS prompted drivers to focus on their lateral control to avoid triggering the system (LeBlanc et al., 2006). However, as the driver used the LDWS and gained comfort, the perceived risk associated with deviating decreased. This decrease in perceived risk may have allowed drivers to feel safer pushing the boundaries of lateral variance, knowing the system would catch if they had gone too far. Specifically, the driver's accepted lateral variance margins would be greater than those they had before the system was introduced. Though this adaptation effect is novel with regards to LDWS specifically, this finding supports the adaptation effects observed in speed and road width work which shows drivers unconsciously adapt their road-width perceptions when presented with wider roads, leading to average lane positions closer to the road edge (Godley, Triggs, & Fildes, 2004; Lewis-Evans & Charlton, 2006). In application to LDWS, the major danger in this adaptation effect is that drivers may be taking on riskier lateral variation as a result of using the system, increasing the frequency with which their vehicle is in a higher-risk road position

compared to when a LDWS was not present. In other words, concern should not be in the concept that the LDWS is so effective at reducing lane deviations that we become reliant on the system and thus perform worse without it; concern should be in the concept that LDWS may subtly change drivers' subconscious perception of the driving environment such that they deviate more than they would if they had not had a system in the first place. Thus, when the LDWS is ON, drivers are more reliant and perceive the lane boundaries as greater (wider) than they had without the system, therefore, they may be more likely to drive closer to the lane boundaries.

With similar reasoning as above, the observed higher number of deviations in ON sections may be associated with factors of reliability, complacency, trust in the LDWS and/or learning of actual lane boundaries through the perception-action feedback loop. When first introduced in this study, the LDWS was reliable and relatively frequently triggered due to the complexity of the course design. According to Stanton and Young's theory, frequent exposure to a high reliability system will lead to trust in the system (Stanton & Young, 2000). Using a similar methodology as Breyer et al. (2010), where they saw 77% of their participant population report acceptance and feelings of safety with a LKS, our participants may have become accepting and trusting of the LDWS when it was presented reliably. With this trust, drivers may have become more complacent in actively monitoring their vehicle's lateral movement, and resultantly, became increasingly more reliant on the LDWS to catch when they drifted too far. Instead of focusing attention on keeping the vehicle within the lane, drivers may have become more variable in their lateral positioning when the system was ON and thus triggered the system more frequently. When conceptualized with the previously suggested LDWS-induced shift in

accepted-risk level, a concerning combination is formed; drivers are now reliant on the system with a higher risk-tolerance for “safe” lateral positions.

Now this conclusion prompts two further questions: 1) if it is the case that LDWS leads to reliance and/or adapted higher zero-risk acceptance levels, then should we see increased deviations, and thereby triggering of the system, over time? 2) why has this effect not been seen in previous work (e.g. Breyer et al., 2010)? First, adaptation to the system over a longer period of time may possibly lead to more deviations and thereby, more frequent triggering of the system, however, this is not necessarily what should be expected. The implications from the adapted lateral risk margins are that the amount of time a driver spends within physical range of the lane-boundary may be greater- not necessarily enough to trigger the LDWS. Second, previous research may not have identified this effect due to lack of sensitivity, as majority of lane keeping analyses compare aggregated means of performance over the course of whole drives with possible other confounding factors. This thesis utilized simulation to create sufficiently challenging courses (to observe frequent lane departure), with the additional benefit of direct comparability between the courses. Thus, the analyses in this thesis directly compared specific road sections where the systematically manipulated factor was solely LDWS activity, allowing for a detailed review of its effects on lane keeping performance. Moreover, similar work has typically just compared performance of driving with LDWS to an original baseline course. As suggested here, if adaptation occurs with the use of LDWS, the effect would not be apparent in comparing back to a baseline course, as the adaptation effects were not yet experienced. Rather, a new baseline (driving without LDWS, but after exposure to using the system) would need to be

compared to driving with LDWS in order to effectively compare performance with and without LDWS.

With regards to short term behavioural adaptation associated with audio cue type, we initially hypothesized that after using LDWS, both warning audio cues would become equally effective and therefore show similar adaptation effects. Contrary to this hypothesis, we first found that overall, rumble cues showed inferior performance to beep cues in specific elements: the rumble cue lead to significantly more deviations and longer deviations regardless of LDWS activity in both the behavioural adaptation analyses. As explored in the first part of this discussion, rumble cues may have been less effective as a warning signal due to their potential to be more easily adapted to and this may have been a function of masking and/or less aggressive nature of the cue. Similarly here, the rumble cue may have further exacerbated adaptations of heightened acceptable risk levels since the cue was so non-threatening. Compared to the beep cue, triggering the LDWS when it emitted a rumble cue may have perpetuated the conception that hitting the lane boundary was a less high-risk event, allowing adaptation of increased accepted-risk levels to occur more quickly and/or more severely than it did with the beep cue. Moreover, the rumble also showed significantly larger deviations in the ON sections compared with the OFF sections within the LDWS Intermittent drive analysis, while the beep cue showed no significant difference. In combination with greater adaptation effects associated with the rumble cue and its overall inferior effectiveness in eliciting quick reactions, the rumble cue may have actually worsened lateral control, accounting for the larger deviations seen in the ON segments of the LDWS Intermittent drive.

In addition to the above findings, an age interaction was seen in the comparison of ON in the LDWS drive vs. OFF in the LDWS Intermittent drive, showing longer deviations in older adults in the OFF sections. This finding is understandable, as older drivers appeared to benefit from LDWS, which alerted and prompted them to quickly return to their lane once they began to deviate. As such, in the OFF sections, there was no LDWS to inform about deviation events and thus the associated time of deviation was longer in older adults. A main effect of age was identified in the comparison of ON vs. OFF within the LDWS Intermittent drive, such that overall, older drivers showed more deviations than younger adults. This result, however, is inconsistent with our previous analyses showing no significant difference between number of deviation in younger and older drivers. A possible explanation for this finding could be that younger adults were perhaps overall better adapted to the driving task and/or use of the LDWS system. Future work could consider more precisely the effects of prolonged experience or practice effects as a function of age.

It must be noted that while this study makes effort to account for practice effects through additional analysis, the possibility of said effects could not be completely isolated. Repetitive use of Course 2 and learning effects of driving the simulator itself may have confounded results; even with the taken measures it was difficult to tease out whether significant differences between the ON and OFF sections were solely due to a short-term adaptation to the use of LDWS or practice effects. When reviewing the adaptation results of this study it was important to take this confound into consideration. With this in mind, results from the practice effects analyses showed no significant difference in dependent measures between the LDWS and LDWS intermittent drive, suggesting the adaptation-related results were not merely a product of practice effects.

To summarize, our initial adaptation hypothesis suggested that drivers would become reliant on the LDWS system to perform well thereby demonstrating detriments to performance when it was unexpectedly intermittently turned off. However, our results revealed unanticipated adaptation effects showing the opposite effect, such that poorer lane keeping was observed when the LDWS was turned on, but under general conditions for which it was unreliable. These findings imply that there is a negative adaptation to the continued use of LDWS itself. With regards to cue effectiveness, the rumble cue lead to more deviations and longer deviations but there was no significant difference between the ON and OFF sections. On the other hand, a significant effect indicated rumble cues may have had a specific detrimental effect on the magnitude of deviations when the LDWS was turned on, in comparison to the beep cue. Age effects indicated older adults showed longer deviations in OFF segments, which may be attributed to slower reaction times to realizing they were deviating when the LDWS was not present.

5.2 Conclusions

In this thesis, I investigated the effects of LDWS based on two audio warning cues (beeps vs. rumbles) in older and younger drivers. Drivers completed four courses (Acclimatization, Baseline, LDWS, LDWS Intermittent) using a 6-axis motion simulator system and car-mock up in a virtual reality dome. Lane keeping performance was evaluated in each of the drives where LDWS activity was selectively inactive, active, or intermittently inactive. Performance effects were analyzed in both warning cue groups and both age groups using the number of deviations, time of deviations, magnitude of deviations, and velocity. Using a data analysis design where

segments of the courses were directly compared allowed for detailed evaluation of the potential adaptation effects of LDWS use.

As initially hypothesized, the results of this work indicated that initial introduction of LDWS was effective in reducing frequency, duration, and magnitude of deviations from road lane boundaries. Initially, both meaningful (rumble) and non-meaningful (beep) audio cues were effective in producing better lane keeping outcomes, however, with longer exposure to the LDWS, the rumble cue showed less effectiveness in reducing number of deviations compared to the beep cue. Additionally, with use, the rumble cue lead to less effective mitigation of time of deviation and magnitude of deviations compared to the beep cue.

Contrary to initial hypotheses, over a short period of driving with LDWS, there was evidence of negative adaptation effects where more deviations were seen in segments where the LDWS was ON compared to segments where the LDWS was OFF. These results may have been a result of LDWS prompting greater awareness of the actual lane boundaries, allowing drivers to subconsciously increase their accepted-risk level of lateral movement (i.e. drive with greater lane margins). Interestingly, this adaptation effect may have been perpetuated by use of the rumble cue, which showed particular impact in leading to larger deviations with the LDWS active, compared to when it was inactive. As opposed to the original hypothesis suggesting LDWS would lead to over-reliance and therefore worse performance in the OFF sections, no indication of over-reliance was observed.

While the original hypotheses predicted older adults would show greater effectiveness from LDWS compared to younger adults, the only significant difference among driver populations

was greater effectiveness in reducing time of deviations on curved road segments for older drivers. No differences among effectiveness of audio cue type or adaptation were specifically identified in the older driving group. While not significant, differences among older and younger drivers in all dependent measures showed relatively worse performance in older adults (more, longer, and larger deviations). While the magnitude of initially improved lane keeping performance and resulting adaptation effects were not significantly different than their younger counterparts, older drivers exhibit age-related deficits and thus extra consideration for implementation of LDWS should be taken in this driver population.

Chapter 6

6.1 Limitations

There were several limitations identified throughout the completion of this study. First, with regards to warning cue type, there is consideration for the fact that while the rumble cue was chosen to be a “meaningful” icon sound, there are issues with ecological validity of the cue. The cue’s referent event is driving over a rumble strip on a road shoulder, which indicates lane departure through both vibration of the car and sound of the tires on the strip. In using a rumble strip sound, without the natural accompaniment of vibration, the logic of a rumble strip sound being an inherently meaningful cue may be flawed. With this in mind, and with consideration for the new multimodal cueing systems begin developed for LDWS, a future experiment using multimodal and congruent cues would be useful to more accurately compare a meaningful warning cue to a completely non-meaningful cue. In addition, the testing of various types of earcons and icons with equitable acoustic properties would allow for a more comprehensive analysis of the effects of meaningful vs. non-meaningful sounds as LDWS warning cues.

Second, there are issues with the participant sample size. Due to a convenience sample and high attrition rates associated with simulator sickness, the sample of participants with useable data sets was fairly small. Similarly, given the high attrition rate among older adults, results of this study regarding age differences may accompany bias; the older adults who were able to complete the study may exhibit superior mental and physical durability to challenging driving tasks compared to the general older driver population. Thus, the sample of older adults used in this study may not be the most general representation of older adults on real roads. While results

showed significance, a larger sample size would provide more power to the analyses and further support for the generalizability of these results across driver populations. Further, implementation of a less challenging driving task may allow for more participants to complete the study while still maintaining a task which is complex enough to see natural deviation events.

Possible practice effects due to repetition of driving the course may have confounded results.

Drive orders could not be counter-balanced as one of the main goals of this experiment was to observe aftereffects of LDWS exposure, thus the drive order of baseline, then LDWS, the LDWS Intermittent, was strategically selected. Attempts to mitigate this issue included staggered start positions within the course, selection of a course with limited defining features, and analyses run on the end and start segments of the consecutive courses to compare practice effects. However, practice effects are cumulative and as such, were not fully accounted for in the practice effect analyses. In future work, a completely counter-balanced, within-subjects design could be utilized to account for any possible practice effects, heterogeneity among participants, and allow for within-subjects comparison of audio cue types to increase sensitivity. Alternatively, additional control groups for comparison to each sound cue group could be tested to show experimental effects without confounding practice effects.

Finally, there are several issues with use of virtual reality simulation to study that impacts the generalizability and translatability of these findings to real-life driving scenarios. Virtual reality encompasses unique visual and perceptual-motor coupling, and human-machine interactions due to differences in sensory misperceptions (e.g. spatial and motor feedback) compared to what would be experienced in real-life driving. As such, adaptation to using the simulation system

may confound the adaptation effects seen in this experiment regarding lane keeping (i.e. learning of the spatial boundaries within the virtual reality environment rather than specific to the driving scenario per se). While there has been studies that show the usefulness of studying underlying driving mechanisms with simulation (Boyle & Lee, 2010), these fundamental differences of virtual reality may affect the applicability of results. This experiment attempted to mitigate these effects by focusing on *relative* validity within the simulation scenarios – comparing conditions within the simulations rather than comparing to performance in the real world. Relative validity within simulation has been indicated to possibly have greater importance than absolute validity between the simulation and real road environment (Godley, Triggs, & Fildes, 2002). To increase translatability and generalizability, future attempts to study the results seen in this experiment could be completed on a newer driving simulation platform with increased real-world likeness or in a controlled field study.

6.2 Future Directions

Over the course of the following months Toronto Rehabilitation Institute will implement an upgraded facility for driver testing known as DriverLab. DriverLab will feature a full-scale car inside a 360° virtual reality dome with 7-axis of motion (6-axis from the motion base, and an additional degree of freedom from a turntable base under the car). As mentioned in the limitations of this study, there are several technology- associated barriers with virtual reality, such as simulator sickness and generalizability to real-world driving. The implementation of the new driving simulator will be designed to help mitigate both of these issues. Through the use of the additional motion range, upgraded visual projection and full-scale car, the realism of the

simulator will be closer to real-life driving conditions and is designed to help mitigate sensory discordance, thereby reducing likely-hood of simulator sickness.

With access to the new facility, and with consideration for the important adaptation effects seen in the current experiment, further experimentation regarding this topic could be explored. A larger scale data collection period could be completed, aiming to test approximately 20-40 drivers in each older and younger group, increasing power of observed effects. As touched on in the limitations section, alterations to the methodology could be made to feature a with-in subjects design, increasing sensitivity and accounting for practice effects. Moreover, there could be expansion of the cue types tested throughout the experiment. More recent LDWS designs feature multimodal cues, and recent research has focused on investigating the use of various warning types in isolation and in combination. Particular interest for haptic and audio-haptic warnings could be investigated- manipulating cue properties such as source location, strength/intensity, duration of cue etc.

Additional future directions for this work could include further in-depth analysis of the lateral position of the simulated vehicle throughout the LDWS and LDWS Intermittent drive. In completing this analysis, we could explore the proposed reasoning of increased road-width perceptions in relation to the observed results of negative adaptation. Possible experimentation with varying road-lane widths could be completed to further evaluate the variability of adaptation effects.

Analysis of the collected driving comfort and personality questionnaires in relation to each of the results presented in this thesis should be conducted. While outside the realm of the current work,

factors or driver personality, risk-taking tendencies, and comfort with driving skills may play a role in the magnitude and direction of adaptation effects from using LDWS. Moreover, results from the analysis of these questionnaires could reveal information regarding the impact of driver characteristics on effectiveness of audio cue warnings in LDWS. Selection of these particular questionnaires was based on their use in the Rudin-Brown & Noy (2002) study which initially implied LDWS may potentiate negative adaptation through over-trust (Rudin-Brown & Noy, 2002). Seeing as the results from this thesis indicate negative adaptation to LDWS, albeit in a different manner than the previously mentioned study, it would be useful to investigate whether the observed effects by Rudin-Brown & Noy (2002) were also factors in this work.

In addition to expansion of LDWS focused research, future work could include similar experimentation for other ADAS of interest. As vehicle development becomes more focused on autonomy, various new ADAS are being developed, with little research to back up their effectiveness. As seen in this thesis, simulation experiments can be useful in highlighting sensitive changes to driver behaviour when using ADAS- thus more experimentation, utilizing similar methodology, could be conducted to evaluate the use of new systems prior to their widespread implementation.

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Appendix 2: Driving Comfort Scales (Myers et al., 2008)

Driving Comfort Scales

Please rate your level of comfort by choosing one option from the scale (0, 25, 50, 75 or 100 %) and checking the box beside each situation.

If you do not normally drive in the situation, imagine how comfortable you would be if you absolutely had to go somewhere and found yourself in the situation.

In your ratings, consider confidence in your own abilities and driving skills, as well as the situation itself (including other drivers).

Assume **normal traffic flow** unless otherwise specified.

‘How **comfortable** are you driving in the **daytime**...?’

Comfort Level	Not confident		Moderately Comfortable		Completely Comfortable
	0%	25%	50%	75%	100%
1. In light rain?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
2. In heavy rain?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3. In winter conditions (snow,ice)?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
4. If caught in an unexpected or sudden storm?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
5. Making a left hand turn with no lights or stop signs?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Comfort Level	Not confident		Moderately Comfortable		Completely Comfortable
	0%	25%	50%	75%	100%
6. Pulling in or backing up from tight spots in parking lots with large vehicles on either side?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
7. Seeing street or exit signs with little warning?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
8. On two lane highways?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
9. Keeping up with the flow of highway traffic when the flow is <u>over</u> the posted speed limit of 100 km/h (60 miles/h)?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
10. With multiple transport trucks around you?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
11. When other drivers tailgate or drive too close behind you?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
12. When other drivers pass on a non-passing lane?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
13. When other drivers do not signal or seem distracted?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Now we would like you to rate your level of comfort when driving in the following situations **at night**.

Even if you **do not normally drive at night**, imagine that you were out in the afternoon, got delayed and it was dark on your way back.

In your ratings, consider confidence in your own abilities and driving skills, as well as the situation itself (including other drivers).

‘How **comfortable** are you driving **at night** ...?’

Comfort Level	Not confident		Moderately Comfortable		Completely Comfortable
	0%	25%	50%	75%	100%
1. In good weather and traffic conditions?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
2. In light rain?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3. In heavy rain?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
4. In winter conditions (snow,ice)?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
5. When there is glare of reflection from lights?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
6. In unfamiliar routes (different areas), detours or sign changes?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
7. Making a left hand turn with no lights or stop signs?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Comfort Level	Not confident		Moderately Comfortable		Completely Comfortable
	0%	25%	50%	75%	100%
8. Pulling in or backing up from tight spots in parking lots with large vehicles on either side?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
9. Seeing street or exit signs with little warning?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
10. On two lane highways?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
11. Keeping up with the flow of highway traffic when the flow is <u>over</u> the posted speed limit of 100 km/h (60 miles/h)?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
12. With multiple transport trucks around you?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
13. Merging with traffic and changing lanes on the highway?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
14. When other drivers tailgate or drive too close behind you?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
15. When other drivers pass on a non-passing lane?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
16. When other drivers do not signal or seem distracted?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Appendix 3: Internality/Externality Questionnaire (Montag & Comrey, 1987)

INTERNALITY-EXTERNALITY

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Appendix

Items for the Driving Internality (DI) and Driving Externality (DE) Scales

No.	Scale	Item stem	No.	Scale	Item stem
1.	DE	Driving with no accidents is mainly a matter of luck	17.	DI	It is always possible to predict what is going to happen on the road and so it is possible to prevent almost any accident
2.	DE	Accidents happen mainly because of different unpredictable events	18.	DI	Accidents happen when the first driver does not take into consideration all the possible actions of the second driver
3.	DE	The driver can do nothing more than drive according to traffic regulations	19.	DI	Accidents happen because the driver does not make enough effort to detect all sources of danger while driving
4.	DE	Accidents happen because of so many reasons we will never know the most important one	20.	DI	Most accidents happen because of lack of knowledge or laziness on the part of the driver
5.	DE	People who drive a lot with no accidents are merely lucky; it is not because they are more careful	21.	DE	If you are to be involved in an accident, it is going to happen anyhow, no matter what you do
6.	DI	The careful driver can prevent any accident	22.	DE	Most accidents happen because the second driver does not pay attention to traffic regulations even when the first driver does
7.	DI	When a driver is involved in an accident, it is because he did not drive as he should	23.	DE	The driver does not have enough control over what happens on the road
8.	DI	When a driver is involved in an accident it is because he did not pay attention to his driving	24.	DE	Most accidents happen because of mechanical failures
9.	DI	Accidents are only the result of mistakes made by the driver	25.	DE	There will always be accidents no matter how much drivers try to prevent them
10.	DI	The driver is to be blamed almost always when an accident occurs	26.	DI	Accidents happen when the driver does not take into consideration all the possible behaviors of pedestrians
11.	DE	It is difficult to prevent accidents in bad conditions such as darkness, rain, narrow roads, curves, and so on	27.	DI	Accident-free driving is a result of the driver's ability to pay attention to what is happening on the roads and sidewalks
12.	DE	Most accidents happen because of bad roads, lack of appropriate signs, and so on	28.	DI	The driver can always predict what is going to happen; that is why there is no room for surprises on the road
13.	DE	It is very hard to prevent accidents involving pedestrians who come out from between parked cars	29.	DI	It is possible to prevent accidents even in the most difficult conditions such as narrow roads, darkness, rain, and so on
14.	DE	Accidents in which children are involved are hard to prevent because they do not know how to be careful	30.	DI	Prevention of accidents depends only on the driver and his characteristics rather than on external factors
15.	DE	It is very hard to prevent accidents in which old people are involved because they cannot hear nor see well			
16.	DI	Accidents happen because drivers have not learned how to drive carefully enough			

Note. These are English translations of the original Hebrew items. Instructions were as follows: You will find in the following some opinions stated by various drivers concerning causes of accidents. Please express your degree of agreement or disagreement with each statement, selecting a number from the following scale: *Disagree very much* (0), *Disagree quite a bit* (1), *Disagree some* (2), *Agree a little* (3), *Agree quite a bit* (4), *Agree very much* (5).

Received July 26, 1985
Revision received January 23, 1987
Accepted January 29, 1987 ■

Appendix 4: Simulator Sickness Questionnaire (Kennedy et al., 1993)

This questionnaire is designed to measure your current **state of well-being**.

In the table below you can find a list of different symptoms. Please indicate truthfully how you feel **at the moment**. To rate the severity of each symptom please tick the appropriate number. You can choose between „not at all“ (0) – „slight“ (1) – „moderate“ (2) – and „severe“ (3). Please make sure to tick every column. There are no wrong or correct answers.

	not at all	slight	moderate	severe
General discomfort	(0)	(1)	(2)	(3)
Fatigue	(0)	(1)	(2)	(3)
Headache	(0)	(1)	(2)	(3)
Eyestrain	(0)	(1)	(2)	(3)
Difficulty focusing	(0)	(1)	(2)	(3)
Increased salivation	(0)	(1)	(2)	(3)
Sweating	(0)	(1)	(2)	(3)
Nausea	(0)	(1)	(2)	(3)
Difficulty concentrating	(0)	(1)	(2)	(3)
Fullness of head	(0)	(1)	(2)	(3)
Blurred vision	(0)	(1)	(2)	(3)
Dizzy (eyes open)	(0)	(1)	(2)	(3)
Dizzy (eyes closed)	(0)	(1)	(2)	(3)
Vertigo	(0)	(1)	(2)	(3)
Stomach awareness	(0)	(1)	(2)	(3)
Burping	(0)	(1)	(2)	(3)

Appendix 5: Fast Motion Sickness Scale (Keshavarz & Hecht, 2011)

FMS-Instruction

Dear participant,

The following scale was designed to measure your general discomfort, in particular nausea. The experimenter will ask you to verbally report how you feel once every minute. We kindly ask that you respond to this question by choosing a single score on the following 20-point rating scale:

0 ----1----2----3----4----5----6----7----8----9----**10**---11---12---13---14---15---16---17---18---19---**20**

NO SICKNESS AT ALL

SEVERE SICKNESS

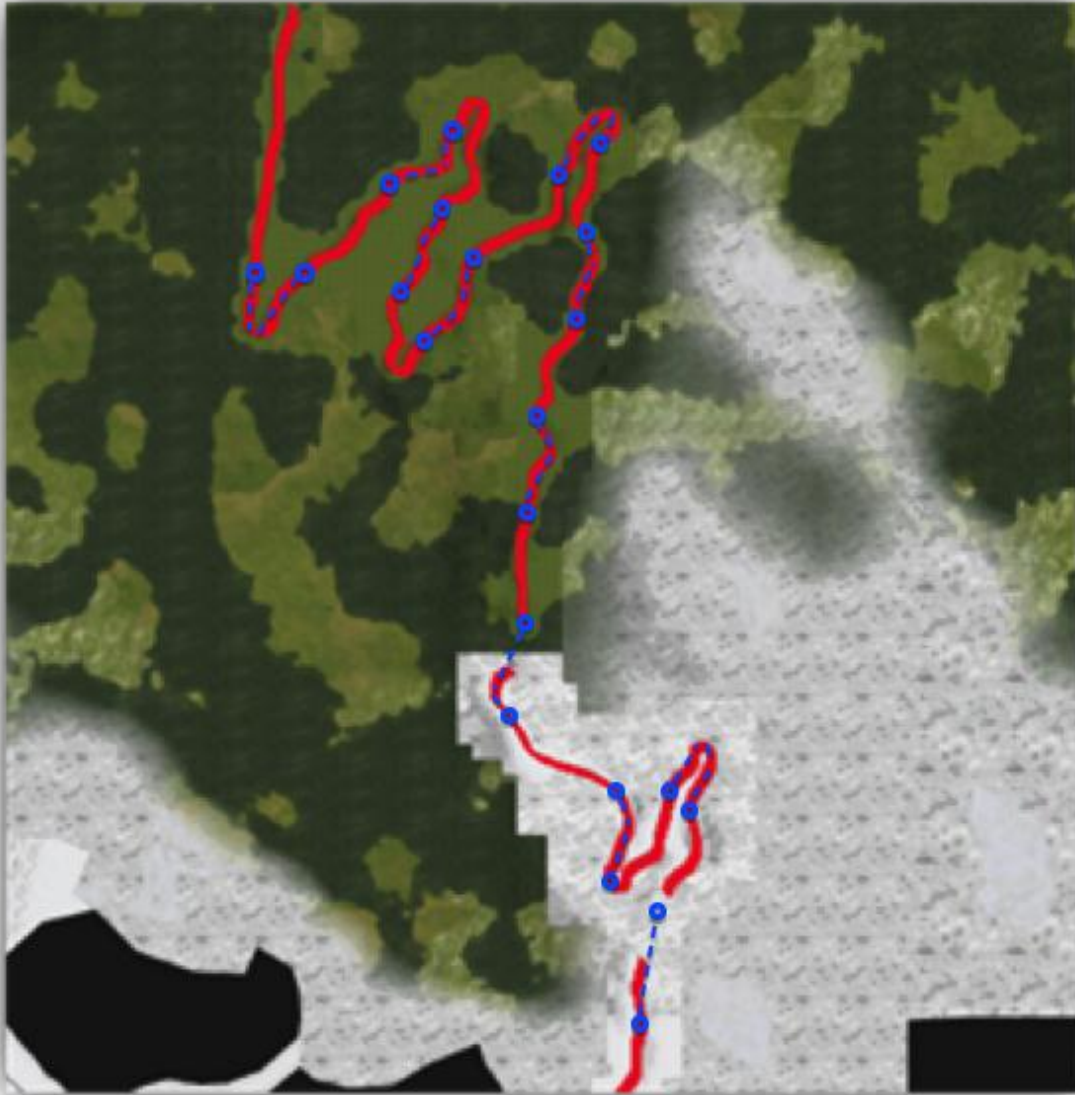
Thus, a score of 0 indicates that you feel perfectly fine, whereas a score of 20 indicates severe nausea to the brink of vomiting.

Please focus in your ratings on currently felt nausea, general discomfort, and stomach problems.

It is very important that you respond honestly. You should also note that any additional feelings, such as fatigue, boredom, excitement, nervousness etc., should not influence your rating.

If you have any questions, please ask the experimenter now.

Appendix 7: Course 2 Trigger breakpoints



Trigger sections indicate LDWS is OFF

*trigger lengths not perfectly to scale (Every 500m)

