Exploring the Influence of Anger on Takeover Performance in Semi-automated Vehicles

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ABSTRACT

As autonomy in vehicles increases, the role of the driver will diminish, moving on to more non-driving related tasks. We are at a juncture at which cars have the ability to drive themselves, but only if the driver is ready to take over control of the vehicle when required (e.g., Tesla autopilot). Therefore, it is important that adequate alerts are used to warn drivers in various contexts to take control back from these semi-automated vehicles. Considerable research has been conducted to design the safest alerts for the takeover transition. However, more systematic research is still required to accurately predict driver responses to different parameters of the alerts. Also, takeover research has not considered drivers' states (e.g., emotions). Anger is one of the emotions that has been shown to impair driver judgment and performance. There is limited research on how anger might influence takeover performance in semi-automated driving. This study aimed to investigate the influence of anger on takeover reaction time and safety by comparing angry and neutral drivers. Additionally, the effects of increased perceived urgency of auditory alarms on takeover reaction time were measured. Data from this research was used to help test mathematical driver behavior modeling using the QN-MHP cognitive architecture. Using a motion-based simulator, 36 participants performed takeovers in semi-automated vehicle on a 3-lane highway. Between takeovers, participants performed a secondary task (i.e., online game) on a tablet. There were no significant differences in takeover reaction time between angry and neutral drivers. However, angry drivers drove faster which can lead to dangerous collisions. Angry drivers took longer to change lanes with lower steering wheel angles. Neutral drivers' slower speeds and higher steering wheel angles indicated that they initiated the lane change earlier, and thus, made safer lane changes. As expected, higher frequency and more repetitions of the auditory takeover displays led to faster takeover reaction times. QN-MHP model predictions of takeover reaction times resulted in a 68.92% correlation with the empirical data collected. The results of this study suggest that angry drivers perform riskier than neutral drivers when taking over control of a semi-automated vehicle. This study is expected to make a significant contribution to research on the influence of emotion, specifically, anger on takeover performance in semi-automated vehicles as well as takeover display design.

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GENERAL AUDIENCE ABSTRACT

Over the last decade, there has been an increasing shift towards the automation of cars. But, this is only made possible in situations where the driver is ready to take over control of the vehicle when required (e.g., Tesla autopilot). Therefore, it is important to use the right alert sounds to warn drivers to take control back from their self-driving cars. There has been a lot of research in designing the safest alerts for taking over control of the vehicle. However, research has not considered the driver's emotions while taking over control of their vehicle. Anger has been shown to be one of the emotions that can impair driver judgment and performance. Limited research has been performed to measure how anger can influence takeover performance. This study compared how angry drivers are different from non-angry (neutral) drivers in their takeover reaction time and safety. Additionally, the effects of a more urgent sounding alert on reaction time were also measured. The data from this research help to validate the predictions of a mathematical model of driver behavior. Thirty-six participants performed takeovers in a self-driving car simulator. While they were driving in the simulator, they also played a game on a tablet.

The results showed that angry drivers and neutral drivers took the same time to takeover. But, angry drivers drove faster which can lead to dangerous collisions. Angry drivers took longer to change lanes with lower steering wheel angles. Neutral drivers started changing lanes earlier because they drove slower and turned more. This meant they drove safer than angry drivers. A more urgent sounding alert led to faster takeover reaction times from both drivers. The mathematical model predictions of takeover reaction time were nearly 70% close to the actual data collected. The results of this study suggest that angry drivers perform worse takeovers than neutral drivers. The findings will help design safer alerts in self-driving cars and also contribute to the design of self-driving cars that consider the drivers' emotional states.

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1. INTRODUCTION

1.2 MOTIVATION

As vehicles move towards more automation, the role of the driver has started to diminish. SAE defined the levels of automated vehicles, from levels 0 to 5, by classifying the driving roles of the driver and the automated vehicle (SAE International, 2014, 2018). At present many car manufacturers are transitioning to level 3 automation (Borenstein, Herkert, & Miller, 2017). The driver's role is moving more towards being a monitor of the system, only taking over control when required in certain situations. The driver will perform "takeovers" of control from the vehicle and "handovers" of control back to the vehicle.

Ensuring the safety of these takeover and handover transitions has become an important priority. It is important that the driver is ready to assume and relinquish control of the vehicle when necessary. Considerable research has been conducted to design better in-vehicle alerts for these transitions (Eriksson & Stanton, 2017; Gold, Körber, Lechner, & Bengler, 2016; Jeon, 2019; Kim & Yang, 2017; Kutchek & Jeon, 2019; Radlmayr, Gold, Lorenz, Farid, & Bengler, 2014; Richie, Offer-Westort, Shankar, & Jeon, 2018; Zeeb, Buchner, & Schrauf, 2015).

The design of a takeover or handover alert is only useful if the driver is able to detect the warning. If the driver is distracted or engaged in another task, the alert may be less effective. Among other sources of distraction, affect can also have a significant influence on the driving performance. It has been widely accepted by psychologists that it is impossible for people to perform actions or think without having the emotional system engaged, even if it is subconsciously (Nass et al., 2005). Driving is a complex task where emotions and affect can have significant consequences. Many studies have already been conducted to measure the influence of affect or emotion on driving performance (Abdu, Shinar, & Meiran, 2012; Bodenhausen, Sheppard, & Kramer, 1994; Chan & Singhal, 2015; Hu, Xie, & Li, 2013; Jallais, Gabaude, & Paire-Ficout, 2014; Jeon, Walker, & Gable, 2014; Jeon & Zhang, 2013).

As with the design of any system, it is important to develop models of behavior to predict any problems that may occur due to interface design or predict any driver reactions to special situations. Many efforts have been made to model driver behavior in the vehicle. Distract-R was used to prototype and evaluate interfaces in vehicles (Salvucci, 2009). Salvucci (2006) also used ACT-R to model driver behavior in vehicles. Jeong and Liu (2017) used the QN-MHP to predict driver eye glances and workload in vehicles. Wu and Liu (2007) used the QN-MHP to model multitask performance in the driving contexts. Many other examples of performance modelling exist (e.g. (Bi, Gan, Shang, & Liu, 2012; Ko, Zhang, & Jeon, 2019; Zhang & Wu, 2018). These models do not usually include affective components as a variable when modelling driving behavior, instead these are added to the margin of error in the models. Future models will need to incorporate these affective influences in them to generate predictions that reflect driving behaviors in the real world.

Only a few studies have looked into the influence of affect on driver performance in takeover situations (Du et al., 2019). By measuring driver takeover performance in angry drivers, this study aims to make a significant contribution to research into emotion and interactions with automated vehicles. Moreover, this study aims to add to the plethora of driver behavior modelling using the QN-MHP and help validate and build on enhancements on the model.

1.2.1 RESEARCH OBJECTIVES

The main goal of this study is to measure the effects of anger on driver performance and safety during a takeover in a level 3 automated vehicles. Additionally, the secondary goal of this study is to test and validate the QN-MHP model to predict takeover reaction times as well as compare predicted takeover reaction times with those of the angry drivers. Therefore, the study aims to answer the following research questions (denoted by prefix 'R').

R1: Does anger have an adverse effect on takeover reaction time in level 3 automated vehicles?

Hypothesis 1 (H1): Reaction time for takeover requests will be longer for participants with induced anger

Hypothesis 2 (H2): The modelled reaction time for takeover requests will be significantly different from the reaction time for angry drivers

R2: Does anger have an adverse effect on lane change safety in level 3 automated vehicles upon a takeover request?

Hypothesis 3 (H3): Lane change duration will be significantly less for angry drivers

Hypothesis 4 (H4): Lane departures will be significantly more for angry drivers

Hypothesis 5 (H5): Glance frequency and duration on the vehicle mirrors will be less for angry drivers as compared to neutral drivers

Additionally, it is expected that perceived urgency for the auditory warning would change based on auditory characterizes: **Hypothesis 6 (H6):** Urgent Auditory alerts with higher pitch range and higher repetitions will show faster takeover reaction time

2. RELATED WORK

2.1 TRANSITION OF CONTROL IN SEMI-AUTOMATED VEHICLES

2.1.1 TAKEOVER AND HANDOVER REQUESTS

SAE defined the levels of automated vehicles, from levels 0 to 5, by classifying the driving roles of the driver and the automated vehicle (SAE International, 2018). Automated Level 3 automated vehicles allow the driver to cede full control of all safety critical functions in certain driving conditions. The driver is still, however, expected to be available for occasional control (National Highway Traffic Safety Administration [NHTSA], 2013). This means that the driver will still have to accept control of the vehicle i.e., takeover control and return control back to the vehicle, i.e., handover control of the vehicle.

Two important tasks in automation are monitoring the system to ensure it performs to expectations and to be ready to resume control when the automation deviates from expectations (Eriksson & Stanton, 2017; Stanton & Marsden, 1996). This highlights the importance of research into the safety of these transitions of control. Consequently, there have been studies into the human factors of these transitions of control. Many studies have focused on measured reaction times to takeover requests (Damböck & Bengler, 2012; Kim & Yang, 2017; Kutchek

& Jeon, 2019), and other variables affecting takeover quality such as frequency of collision occurrences, lane change duration and acceleration (Gold, Berisha, & Bengler, 2015; Gold et al., 2016; McDonald et al., 2019; Radlmayr et al., 2014). Studies have also focused on unimodal and multimodal displays to ensure safe transitions (Jeon, 2019; Politis, Brewster, & Pollick, 2015; Politis, Brewster, & Pollick, 2014; Richie et al., 2018). This study will look specifically at takeover of level 3 semi-automated vehicles in collision avoidance scenarios.

2.2 MULTIMODAL COLLISION WARNING SYSTEMS IN SEMI-AUTOMATED VEHICLES

Research has found that multimodal warnings help drivers perform better in driving situations when compared to unimodal displays. Ho, Tan, and Spence (2006) found that multimodal warnings captured driver attention effectively in demanding situations. Petermeijer, Bazilinskyy, Bengler, and De Winter (2017) showed that multimodal displays should be used over unimodal displays for takeover requests. Politis et al. (2014) used combinations of audio, visual, and tactile modalities and found that as modalities increased, perceived urgency of the warning increased and recognition time decreased. Politis et al. (2015) further showed multimodal displays performed better than unimodal displays in the context of takeover. The present thesis uses a visual and an audio warning for participants as redundancy measures as well as recreating the advised warning modalities.

2.2.1 AUDITORY WARNINGS

As driving is primarily a vision-heavy process, the auditory channel can be used as an alternate or additional line of communication between the driver and vehicle (Richie et al., 2018). Audio's separation from vision allows for concurrent processing of information while limiting any impact on the processing of visual information (Wickens, 2002).

Different types of auditory warnings can be used in the context of takeover in semi-automated vehicles. Auditory icons are made using a representative sound that relates to an object or event (Gaver, 1986), such as the sound of the crumping of paper when a file is deleted in Windows. Earcons are short abstract musical sounds (Blattner, Sumikawa, & Greenberg, 1989) such as the beeps accompanying a public announcement system or the sounds played in phone voicemail. Graham (1999) showed that although auditory icons produced significantly faster reaction times than conventional auditory warnings, drivers suffered from more inappropriate responses for the given situation. Jeon (2019) tested takeover performance for spearcons, earcons, and speech auditory warnings and found that earcons and speech showed the best performance, i.e., lower takeover time in the context of takeover in automated vehicles. For the present study, earcons were chosen as auditory warnings as they enabled comparisons of different acoustic characteristics and their influence on takeover performance.

Auditory Warning Design Characteristics

When it comes to auditory warning design, the perceived urgency of an auditory warning is an important consideration (Haas & Casali, 1995). According to Zhang and Wu (2018), the perceptual processing time for an auditory stimulus is inversely related to the perceived urgency of the sound. It would be in the interest of safety of the driver and passengers that in-vehicle auditory warnings sounded more urgent to the driver.

Existing literature on urgent abstract warning design shows that higher fundamental frequency, and higher pitch range increased perceived urgency for auditory warnings (Edworthy, Hellier, Walters, Weedon, & Adams, 2000). Moreover, urgent warnings show shorter response times (Edworthy, Loxley, & Dennis, 1991). Marshall, Lee, and Austria (2007) showed higher pulse duration and a lower inter-pulse interval lead to increased urgency of auditory warnings.
The design of in-vehicle auditory warnings with a focus on acoustic characteristics and their effects on user perception has been studied and several acoustic criteria have been recommended, such as peak-to-total time ratio, interburst interval, the presence of harmonics, its base (lowest spectral) frequency, and pulse duration (Lewis, Eisert, & Baldwin, 2018).

In summary, the stronger impact of auditory warnings on perceived urgency has been shown with higher fundamental frequency, the presence of harmonics, and rapid temporal changes (Giang & Burns, 2012; Hellier & Edworthy, 1989; Lewis et al., 2018). Faster repetitions of the pulse and higher pitch lead to differences in perceived urgency of a warning (Hellier, Edworthy, & Dennis, 1993). Moreover, auditory warnings having a higher number of repetitions within a fixed time with a higher frequency showed better performance. Finally, fundamental frequency, variations in speed, repetition units, inharmonicity, and the level of pitch range caused variations in perceived urgency of an auditory warning (Edworthy et al., 1991). For this present study, two auditory characteristics that affected perceived urgency were chosen, number of repetitions per second and the number of semi-tones (pitch range). These were chosen because they have been shown to influence perceived urgency and they have also been used along with fundamental frequency to predict driver behavior in takeover (Ko et al., 2019).

2.2.1.1 AUDITORY WARNING LEAD TIMES

Lead time or time budget is an important factor in the effectiveness of takeover requests in level 3 automated vehicles. In a review of different takeover related literature, the mean lead time found to be used among 25 different studies was 6.37 ± 5.36 seconds having a mean reaction time of about 2.96 ± 1.96 seconds. The study also found that 3, 4, 6 and 7 seconds where the most frequent lead times with reactions of 1.14, 2.05, 2.69 and 3.04 seconds respectively (Eriksson & Stanton, 2017).

Gold et al. (2015) compared two lead times, 5 and 7 seconds, and found that although 5 seconds had faster reaction times, it led to harder stops, swerving on the road and failure to check blind spots while switching lanes. The 7 second lead time showed better braking performance, although the vehicle was still in accelerating motion, and therefore not fully in control, suggesting even 7 seconds was not entirely safer. Damböck and Bengler (2012) compared the lead times of 4, 6 and 8 seconds and found that in simpler conditions of takeover, the 4 second lead time led to satisfactory performance but an increase in complexity of a takeover situation led to driver’s requiring longer lead times. Shorter lead times have shown better reaction times but also more collisions and unsafe driving (Mok et al., 2015; Zeeb et al., 2015).

Wan, Wu, and Zhang (2016) compared driver performance for different lead times between 0 and 30 seconds for collision warnings in a connected vehicle context. Using kinetic energy reduction, minimum time to collision, and collision rate as their major dependent variables, the authors concluded that a lead time of 4-8 seconds was best for optimal safety benefit and a lead time between 5-8 seconds gave the best reaction time. It was also concluded that below 2 seconds the kinetic energy of the vehicle was too high for collision avoidance and that above 8 seconds drivers showed a higher collision rate.

In a previous study conducted within the Mind Music Machine Lab at Virginia Tech, we compared 3, 5, 7 and 9 second lead times in the context of takeover in level 3 automated vehicles (Stojmenova et al., in-press). The results suggest that 7 seconds was the optimal lead time which was in line with previous research (Gold et al., 2015; Radlmayr et al., 2014). For the present study, 7 seconds was chosen as the lead time for the takeover warning.

2.2.1.2 AFFECT IN COGINITIVE TASKS

Affect describes distinct constructs that include emotions, feelings and moods. However, researchers tend to use affect as a generic label to include the terms above (Jeon, 2017). For the purposes of this thesis, I shall use the term affect as a wide all catching term for emotions, feelings and moods.

There has been considerable research to see if affect influenced attentional (Fredrickson & Branigan, 2005; Olivers & Nieuwenhuis, 2006; Rowe, Hirsh, & Anderson, 2007) and judgement/decision making tasks (Arkes, Herren, & Isen, 1988; Conway & Giannopoulos, 1993).

Human actions and thoughts are intrinsically related to emotion (Nass et al., 2005). Any interface that ignores a user’s affective state or wrongly reacts to an emotion can have a unfavorable impact on task performance and trust (Brave & Nass, 2003). Affect relevant thoughts can affect information processing, especially if the emotion induces high arousal. This can be positive or negative based on the context (Brave & Nass, 2003).

2.3 AFFECT IN DRIVING

Perception, organization of memory, categorization, decision making, focus and attention can be influenced by emotion and thus influence driver performance (Eyben et al., 2010).

Therefore, it is important to understand how emotions influence driver performance and also which emotions are of importance in this context.

Jeon and Walker (2011) constructed an affect dimension for this exact reason. They extracted Nine affective factors that could explain the influence on driving situations, namely, fear (anxiety), happiness, anger, depression (sadness), curiosity (confusion), embarrassment, urgency, boredom (sleepiness), and relief. They also found that anger was one of the more important and crucial affective states. Driving behavior seems to be influenced by specific emotional states. Anger shows drivers that take more risk, being more aggressive and violate traffic rules more often (Abdu et al., 2012).

2.3.1 EFFECTS OF ANGER IN THE DRIVING CONTEXT

Anger is a negative valence emotion with a high arousal and is commonly experienced during driving (Mesken, Hagenzieker, Rothengatter, & De Waard, 2007). Studies have also linked anger to traffic infringements (Nesbit, Conger, & Conger, 2007).

There is a lot of evidence that anger can degrade driving performance (Jallais et al., 2014; Jeon, Walker, & Gable, 2014; Jeon, Yim, & Walker, 2011). Anger can arise from appraisals of other-responsibility for unfavorable events and a certainty of an event or action. Anger can be thus associated with the perception of less risks in new situations and more perceived control. This influences performance so that angry drivers take more risks, are more certain about decisions and this can lead to errors (Jeon, Walker, & Yim, 2014). Angry drivers are also less likely to be aware of critical information or potential hazards on or off road (Jeon, Walker, & Gable, 2015).

Jeon (2016) conducted an experiment with simulated driving with participants' induced anger and sadness to examine their effects on performance, risk perception, and perceived workload and found that both anger and sadness degraded driving performance. Jeon, Walker, and Gable (2014) showed that an induced angry state can degrade driver situation awareness and performance when compared to a control group. Angry participants consistently showed more errors than neutral participants in most error types. Jeon, Walker, and Yim (2014) measured driver performance and errors in driving while angry and showed that induced anger had negative effects on subjective safety levels and degraded driver performance. Angry drivers also showed more driving errors than fearful drivers. Jeon et al. (2011) studied anger and fear induced drivers and their results showed anger led to more errors regardless of difficulty level and error type. This current study aims to measure how angry drivers perform when compared to neutral drivers in takeover scenarios.

2.3.2 AFFECT INDUCTION IN DRIVERS

The driving task is a long lasting and complicated task which has a lot of complexity over simple judgement and decision-making tasks. In level 3 automated vehicles, the driver can be asked at any point to assume control of the vehicle, and thus, it would be the most appropriate that an affect induction technique that makes the induced emotion last through the duration of the experimental drive.

Autobiographical recall (Bodenhausen et al., 1994) is one method that has been tried and successfully tested in the context of emotion induction for drivers in vehicles (Jeon, 2016; Jeon, Walker, & Gable, 2014; Jeon, Walker, & Yim, 2014; Jeon et al., 2011).

In this methodology, participants are asked to rate their current affective states using a seven-point Likert-type scale. The affective states include the nine discrete adjectives that were reported as important affective states in driving contexts: fearful, happy, angry, depressed (sad), confused, embarrassed, urgent, bored, and relieved (Jeon & Walker, 2011).

Thereafter, the participants have 12 minutes to write a description of a past experience associated with a specific emotion. Participants in a neutral condition write their mundane events of the previous day. The experimenter instructs the participants to remember the memory of the experience as clearly as possible and asks them to visit the experience emotionally again. As a reference, participants are shown two sample paragraphs, of which one is related to driving (See Appendix 9.2.2). After this, the participants write down their experience. If there are more than one experience, they can choose to write about them within the time provided. If they complete the writing before 12 minutes, they are instructed to read their own paragraph and encouraged to revisit that experience as vividly as possible.

After this, the participants fill the emotional Likert scale again. Thereafter, the participant completes the driving task and fill the emotional Likert scale again.

2.4 COGNITIVE MODELLING OF DRIVER PERFORMANCE

2.4.1 PREVIOUS MODELS

Many cognitive models have been used to estimate human cognitive processes and behaviors, such as MHP (Model Human Processor), GOMS (Goals, Operators, Methods, and Selection rules) , EPIC (Executive-Process/Interactive Control), ACT-R (Adaptive Control of Thought Rational) and SOAR (State, Operator, And Result) (Feyen, 2002; Kieras & Meyer, 1997; Liu, Feyen, & Tsimhoni, 2006; Newell & Card, 1985).

2.4.2 QUEUING NETWORK-MODEL HUMAN PROCESSOR (QN-MHP)

The Queuing Network-Model Human Processor (QN-MHP) is a computational architecture that integrates three stages of human information processing – perceptual processing, cognitive processing, and motor processing into three continuous subnetworks (Liu et al., 2006; Zhang, 2017).

Each subnetwork can be thought to be constructed of multiple servers and links that connect these servers. Each server abstracts an area of the brain associated with specific functions, and links represent neural pathways between these functional brain areas. QN-MHP integrates these queueing networks for mathematical modeling and real-time generation of psychological behavior. This neurological processing of stimuli and information is illustrated as passing through routes in the QN-MHP network (Zhang, 2017).

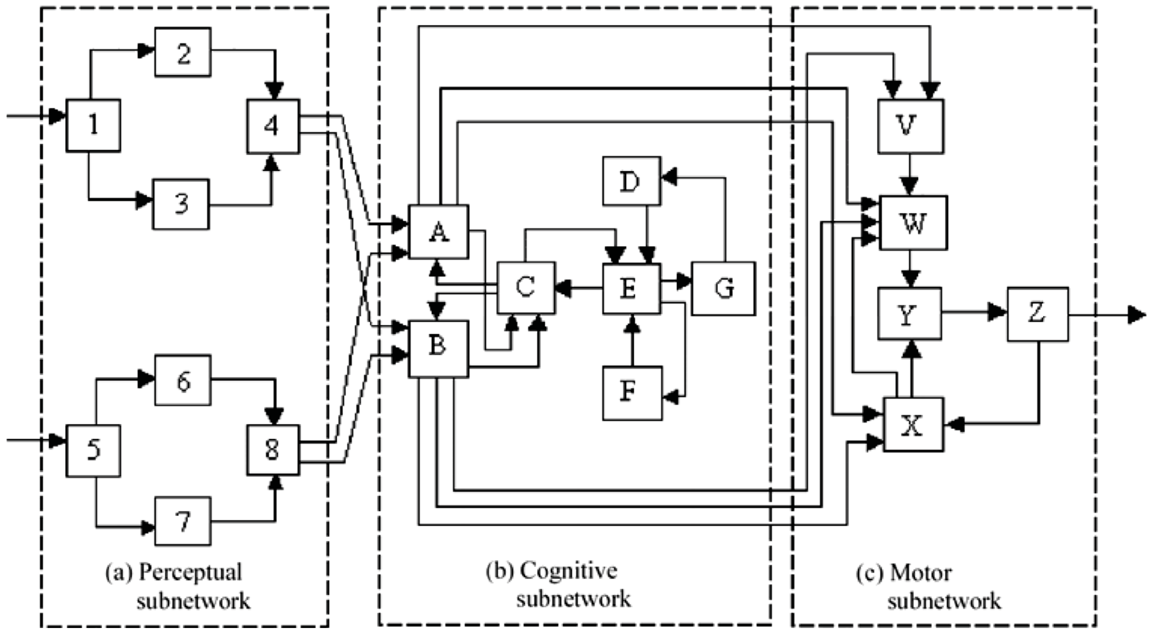


Figure 1: The Queuing Network-Model Human Processor (QN-MHP) Image and description adapted from Liu et al. (2006). (a) Perceptual: 1 = common visual processing; 2 = visual recognition; 3 = visual location; 4 = location and recognition integrator; 5 = sound localization; 6 = linguistic processing; 7 = processing of other sounds; 8 = linguistic and other sounds integrator. (b) Cognitive: A = visuospatial sketchpad; B = phonological loop; C = central executor; D = goal procedures; E = performance monitoring; F = high-level cognitive operations; G = goal selection. (c) Motor: V = sensorimotor integration; W = motor element storage; X = movement tuning; Y = motor programming; Z=actuators. Note: Although not shown in this figure, environmental and device servers receive output customers from server Z and supply input customers to server 1 and server 5

2.4.3 QN-MHP IN THE CONTEXT OF DRIVING

Jeong and Liu (2017) used the QN-MHP to predict driver eye glances and workload for secondary tasks while driving. Guozhen and Changxu (2013) used the QN-MHP to model longitudinal vehicle control. Bi et al. (2012) used the QN-MHP to model single task lateral control and dual task driving with a distracting task. Wu and Liu (2008) used the QN-MHP to model multitask performance and subjective workload in the context of driving.

In most of the modelling the input modalities considered are visual, although there were some exceptions to this (Zhang & Wu, 2017; Zhang, Wu, & Wan, 2016). Ko et al. (2019) used the QN-MHP to model takeover performance to speech and non-speech auditory warnings.

Modelling auditory warning response times using the QN-MHP is advantageous because (1) the QN-MHP model uses well established psychological and neurological evidence, (2) its subnetworks for auditory processing are very detailed, (3) it has been used before for auditory warning modelling, and (4) it can simulate multitasking which is common in driving contexts.

2.4.4 MODELLING REACTION TIME USING QN-MHP

The reaction time for a warning is modelled using the following equation.

$$T_r(i,j) = \sum_{u=1}^{2} PT_u(i,j) \times P_u(i,j,wl,wsm,wt,ws,wr)$$

where *wl* and *wsm* denote warning loudness and warning semantics. *wt* denotes warning lead time, *ws* denotes warning style, *wr* denotes warning reliability. $PT_u(i, j)$ represents the processing time of a stimulus of driver *i* in event *j* though route *u*.

The processing time $PT_u(i, j)$ of a stimulus through a route *u* was modeled by summarizing the time of the stimulus traveling through all the servers on that route *u*.

$$PT_u(i,j) = \begin{cases} T_5 + T_6 + T_8 + T_B + T_W + T_Y + T_Z, & if\ u = 1 \\ T_5 + T_6 + T_8 + T_B + T_C + T_F + T_H + T_F + T_1 + T_2 + T_4 + T_A + T_C + T_W + T_Y + T_Z, & if\ u = 2 \end{cases}$$

where T_k denotes the processing time of the stimulus at Server *k* (*k* =1-8, A,B,C,F,H, W−Z) (Zhang et al., 2016).

The probability of a speech warning traveling the route *u* was modeled by,

1. The probability of choosing a route *u* because of perceived warning urgency P_{wu}, modelled by warning loudness *wl* and semantics *wsm*.

   $$P_{WU}(i,j,wl,wsm) = \frac{1}{2}\left(U(wl) + U(wsm)\right)$$

   where U*(wl)* is the perceived urgency regarding warning loudness, and U*(wsm)* is the perceived urgency regarding warning semantics

2. The probability of choosing a route *u* because of perceived hazard urgency P_{HU}, modelled by warning lead time *wt*

$$P_{HU}(i,j,wt) = \frac{1}{wt}$$

3. The probability of choosing a route *u* because of perceived trust of the warning P_{TR}

$$P_{TR}(i,j,wr,ws) = \frac{1}{2}\,(wr\ +\ \sigma(ws))$$

Where, warnings style is *ws* and warning reliability is *wr*

2.4.5 ENHANCEMENTS TO INCLUDE NON-SPEECH WARNINGS

Based on the literature visited in section 4.3.2.1, and previous studies (Ko et al., 2019), three additional acoustic characteristics were added to the existing QN-MHP model to account for variations in fundamental frequency, number of repetitions of an auditory warning and pitch range of dominant frequencies and their effects on the perceived urgency of an auditory warning. P_{WU} was then enhanced to include these terms as shown below. A new parameter *U(wac)* was added to account for the perceived urgency.

.

$$P_{WU}(i,j,wl,wsm) = \frac{1}{2}\,(U(wl) + U(wsm) + U(wac))$$

$$U(wac) = \frac{1}{3}\,(U(wfreq) + U(wrep) + U(wpit))$$

Where *U(wfreq)* is the urgency for fundamental frequency, *U(wrep)* is the urgency for the number of the repetitions per second, and *U(wpit)* is the urgency for the pitch range of dominant frequencies (Ko et al., 2019).

$$U(wfreq) = \left(0.0255 \times F_{fundamental}\right) + 61.8383$$
$$U(wrep) = \left(30.2295 \times N_{repetitions\ per\ second}\right) + 45$$
$$U(wpit) = \left(1.8553 \times D_{pitch}\right) + 42.6053$$

Where $F_{\text{fundamental}}$ is the level of the fundamental frequency of an auditory warning, $N_{\text{repetitions per scond}}$ is the number of repetitions per second of the auditory stimulus, and D_{pitch} is the difference between the highest and the lowest pitch in semitones (Ko et al., 2019).

In this study, I will measure the differences in modelled reaction time by varying the fundamental frequency and number of repetitions, with the expectation that higher perceived urgency would result in faster modelled reaction times. I will then compare the results with the empirical data collected for angry and neutral drivers and discuss differences if any arise.

3. METHOD

3.1 EQUIPMENT

The study was conducted in a motion-based driving simulator assembled by Nervtech. It consists of a car seat, a steering system and sport pedals. Visuals were be displayed on a triple-screen configuration, which covers a 120° horizontal field of view and consists of three equal curved 48-inch HD TVs. The driving scenarios were developed using SCANeR Studio, a driving simulation software program developed by AV Simulation, run on a computer with an i7 - 8086K CPU and Nvidia GTX 1080 graphics card. Tobii Pro Glasses 2 was used for eye tracking in the vehicle.

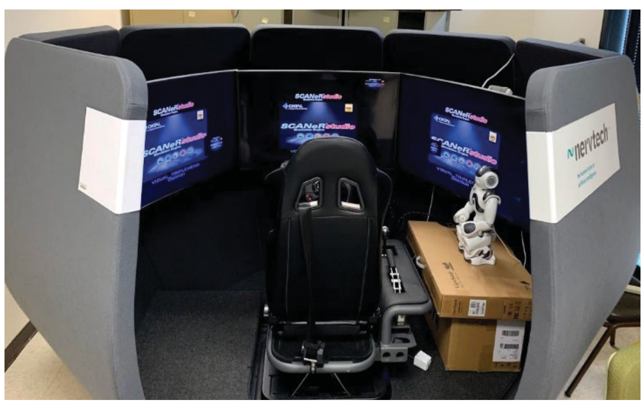


Figure 2: Nervteh Simulator running SCANeR Studio

Figure 3: Tobii Pro Glasses 2

3.2 DRIVING SCENARIO

The driving scenarios involve driving on a three-lane highway with 110 km/h (70 miles/h) speed limit. The visibility was lowered to approximately 100 meters using fog. The participant started their journey on the automated driving system (ADS) on the middle lane of a three-lane highway. At randomly assigned times, the road had an obstacle presented to the participant, at which time, a takeover request was generated where they had to take over control of the vehicle using either the steering wheel or the brake pedal. After avoiding the obstacle by switching lanes, participants were asked to hand over control to the vehicle. Each participant drove 3 laps of approximately 9 minutes each. Each lap consisted of 3 randomly assigned obstacles. In total, each participant experienced 9 different (3x3) warning sounds.

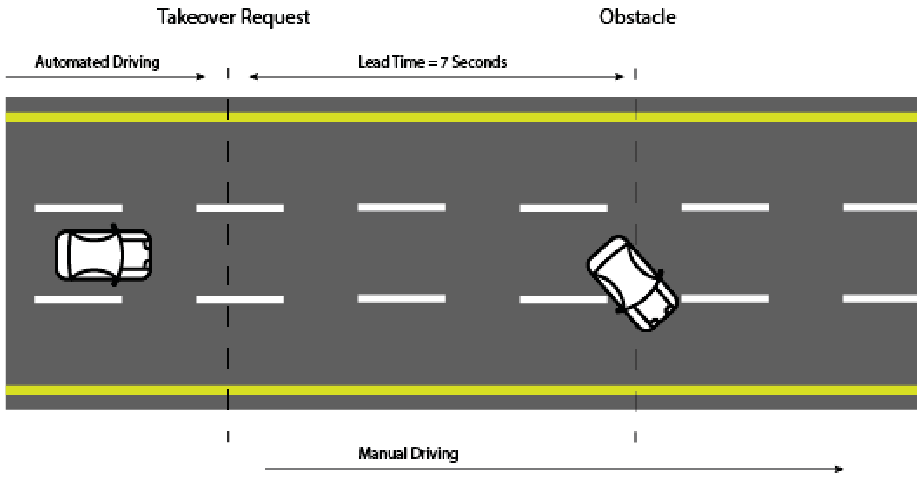


Figure 4: Driving Scenario

Figure 5: Image of participant in driving scenario

3.3 WARNING SOUND DESIGN

The National Highway Traffic Safety Administration (NHTSA), laid down its guidelines for the human factors of level 2 and level 3 automated vehicles. For auditory warnings, it was recommended that the auditory warning included frequency components in the range of 500-2500 Hz (Campbell et al., 2018). For this present study, the pitch range was set to 7 semi tones. Loudness was set to 70 dBA which was well above the ambient noise and below the guideline of 90 dBA (Campbell et al., 2018).

For auditory alerts' urgency cues can help provide information regarding the criticality of a situation or when quick responses are needed. According to the NHTSA, different characteristics of an auditory alert can be modified to influence its salience and perception of urgency. Using faster auditory signals (e.g., 6 pulses per second), and a higher fundamental frequency help improve perceived urgency of an auditory alert (e.g., 9 semi-tones) (Campbell et al., 2018). For the auditory alerts being used in the present study, the sound characteristics described in section **4.2.2.1** (The number of repetitions per second and the fundamental frequencies) were used. The number of repetitions was varied between three levels, 1 per second, 4 per second and 8 per second. The fundamental frequencies were varied between three levels set at 523.25 Hz, 880 Hz and 1480 Hz. There was a total of 9 sounds (3x3 levels) displayed to the participant.

Each sound was played at the start of the takeover request and stop when takeover is complete. Each participant experienced 9 combinations of the two factors: number of repetitions per second and fundamental frequencies as shown below in Table 1. The order of the sounds A-I will be counter balanced using a Latin square for 18 participants for each of the two groups of participants (Neutral and Angry).

1. Number of Repetitions per second (Factor R)
    a. 1 per second (R1)
    b. 4 per second (R2)
    c. 8 per second (R3)
2. Fundamental Frequencies (Factor F)
    a. 523.25 Hz (F1)
    b. 880 Hz (F2)
    c. 1480 Hz (F3)

Table 1: Sound Design

Sound Designs

Sound A	F1R1
Sound B	F1R2
Sound C	F1R3
Sound D	F2R1
Sound E	F2R2
Sound F	F2R3
Sound G	F3R1
Sound H	F3R2
Sound I	F3R3

3.4 EXPERIMENTAL DESIGN

3.4.1 PHASE 1: COGNITIVE MODELING & PILOT

Phase 1 involved modelling driver reaction time to the takeover request. The values of *U(wac)* were calculated using the fundamental frequency, number of repetition and pitch range for each sound design (A-I).

In parallel, a pilot study was conducted to test the emotion induction technique and conduct manipulation checks between two groups of participants, the first whose participants will be engaged in a non-driving related task and the second, whose participants will not be engaged in a non-driving related task.

3.4.2 PHASE 2: SIMULATOR STUDY & MODEL VALIDATION

Phase 2 involved the completion of the driving simulator study for the two main groups of participants, angry and neutral participants. The empirical results were then compared to the results from the phase 1 modelling.

3.4.3 INDEPENDENT VARIABLES

3.4.3.1 AFFECT INDUCTION

Participants experienced either induced anger or neutral emotions while participating in the study. Each participant went go through the same autobiographical recall method but the neutral participants were asked to write down non-emotion inducing mundane memories whereas the anger induced participants were asked to write down recent memories that were emotion inducing.

3.4.3.2 SOUND CHARACTERISTIC: NUMBER OF REPITITIONS

Number of repetitions were varied between 3 levels, 1/second, 4/second and 8/second. Each participant will experience each level of this independent variable.

Number of Repetitions per second (Factor R)

a. 1 per second (R1)
b. 4 per second (R2)
c. 8 per second (R3)

3.4.3.3 SOUND CHARACTERISITC: FUNDAMENTAL FREQUENCY

Fundamental frequencies were varied between 3 levels. Each participant will experience each level of this independent variable.

Frequency levels (Factor F)

a. 523.25 Hz (F1)
b. 880 Hz (F2)
c. 1480 Hz (F3)

3.4.4 DEPENDENT MEASURES

3.4.4.1 DEFINITIONS

i. **Time to Collision**

Time interval, usually measured in seconds, required for one vehicle to strike another object if both objects continue on their current paths at their current accelerations.

ii. **Lead Time**

Time to collision of the vehicle at the moment of time a takeover warning has been placed.

iii. **Lane Change**

Lateral movement of a vehicle from (1) a merge lane into a lane of a traveled way, (2) one lane of a traveled way to another lane on the same traveled way with continuing travel in the same direction in the new lane, or (3) a lane on a traveled way to an exit lane departing that traveled way (SAE International, 2015).

iv. Affect

Affect can be described as several distinct relevant constructs that are frequently treated as interchangeable. They include emotions, feelings, and moods(Jeon, 2017). For the purposes of this thesis, affect will refer to the experience of an emotional state such as anger, sadness, happiness among others.

v. Gaze

The area of interest (AOI) to which the eyes are directed.

vi. Glance

The maintaining of visual gaze within an AOI, bounded by the perimeter of the AOI; comprised of at least one fixation and a transition to or from the AOI.

3.4.4.2 TAKEOVER REACTION TIME

i. Takeover Reaction Time

The response time from the warning signal until either the brake is moved 10% or more or steering wheel angle is changed +/- 2 degrees. The response time was measured in milliseconds (Gold et al., 2015).

ii. Braking Reaction Time

The response time until the brake is moved from the warning signal until the brake pedal is moved 10% or more. Measured in milliseconds.

iii. Steering Reaction Time

The response time from the warning signal until the steering wheel angle is changed +/- 2 degrees. Measured in milliseconds.

3.4.4.3 TAKEOVER QUALITY

A lane change is defined as the lateral movement of a vehicle from one lane of a traveled way to another lane on the same traveled way with continuing travel in the same direction in the new lane. Takeover quality can be measured by the following factors. According to SAE J2944, Lane change can be detected using gaze of the driver or when the vehicle starts to move laterally towards another lane and crosses it or a combination of the two or more methods (SAE International, 2015). For this study the movement of the rear-center axle of the vehicle was chosen as the point from whivh lateral motion was measured. Therefore, lane changes were mentioned from the time the auditory warning was sounded until the rear-center axle of the vehicle crossed the lane lines.

i. **Lange Change Duration**

Time interval, measured in milliseconds, over which a vehicle changes from one travel lane to another (SAE International, 2015). This was measured using **simulator data.** Lane change was measured using simulator data on the position of the vehicle's central rear axle relative to either one of the two lanes. Once the center of the rear axle of the vehicle switches from one lane to another, it is considered a lane change.

ii. **Glance Frequency & Duration**

Glance Frequency can also be used to measure how often participants looked at the mirrors, the new driven lane, and the original lane when induced with emotion. The glance duration will give information if a participant spends more time on a specific area of interest.

iii. **Steering Wheel Angle**

Steering wheel angle changes during the lane change, including average, maximum and minimum.

iv. **Number of Lane Departures**

Count of the number of times usually reported for a particular distance, often per 100 mi or 100 km, when some part of the vehicle is no longer in the travel lane. In this case , the total number of lane departures in experimental run was used(SAE International, 2015).

v. **Speeding**

Average speed during takeover. Higher speeds can possibly cause unsafe driving.

vi. **Braking Deceleration and Jerk**

The deceleration caused jerk can have a negative impact on passengers in the vehicle, therefore this may be a useful measure of safety.

vii. Takeover Type

The type of takeover response i.e., braking or steering.

viii. Takeover Success Rate (Collisions)

The success rate (number of collisions) was also be measured.

3.4.5 CONTROL VARIABLES

3.4.5.1 DRIVING SIMULATOR

Level 3 semi-automated vehicle simulated in a motion-based driving simulator designed and assembled by Nervtech.

3.4.5.2 DRIVING SCENARIO

Three Laps in driving simulator with 3 obstacles per lap. The drive was conducted on a Three lane highway with fog setting visibility to 100 m.

3.4.5.3 MULTIMODAL WARNING

Auditory Warning Pitch Range

A high pitch range of 7 semi-tones was chosen.

Auditory Warning Loudness

Auditory warning will be set to 70dbA.

Warning Lead time

Auditory & visual warnings will be given 7 seconds before collision.

3.5 PARTICIPANTS

3.5.1 PARTICIPANT RECRUITMENT

IRB #19-088 was used for data collection with human participants. The study was advertised in Virginia Tech through the use of mailing lists and flyers. Each participant was compensated $10 for their time. Pre-requisites for the study will be,

1. Active driver with valid US driver’s license
2. More than 2 years of driving experience
3. Age 19+

4. Normal Vision and Hearing (Participants with eyeglasses omitted unless they had contact lenses)

Pregnant women and prospective participants who had issues with nausea were be omitted from the study. In total 36 participants were recruited for the study, 18 with induced emotion and 18 without. Each session took approximately one hour.

Table 2: Study Design

	Fundamental Frequency								
	F1			F2			F3		
	Number of Repetitions								
Affect Induction	R1 Obstacle 1	R2 Obstacle 2	R3 Obstacle 3	R1 Obstacle 4	R2 Obstacle 5	R3 Obstacle 6	R1 Obstacle 7	R2 Obstacle 8	R3 Obstacle 9
Induced - Angry (A1)	S1…S18	S1…S18	S1…S18	S1…S18	S1…S18	S1…S18	S1…S18	S1…S18	S1…S18
Control - Neutral (A2)	S19…S36	S19…S36	S19…S36	S19…S36	S19…S36	S19…S36	S19…S36	S19…S36	S19…S36

3.6 PROCEDURE

The experiment lasted approximately an hour and participants were allowed to ask for breaks at any time during the experiment. If participants were injured or fatigued from the experiment, they could leave the experiment with no consequences. No participant left the study due to injury or fatigue. A total of 37 participants took part in the study of which one participant could not finish the study due to technical issues. First, the participants were briefed about the study and were asked to give their consent for participation. If the participant consented to be a part of the study, they were brought to the driving simulator and allowed to adjust the seating for comfort.

Then, the participant was briefed about the next steps in the experiment and given the Demographics Questionnaire to fill. When the participant was ready, the experimenter prepared the participant for the experiment by attaching the eye tracker (Tobii Pro Glasses 2).

When the participant was comfortable and ready to begin, the experimenter started the simulator. The participant was allowed to drive in the simulator to become familiar with its working. Before the actual study began, participants had a short (2-3 minute) driving session as a simulation sickness test run. Before and after this run, they filled out the simulation sickness questionnaire to screen out vulnerable populations. This session also allowed them to get familiar with the task.

Once successfully completed, the experimenter began the study. Participants were asked to rate their current affective states using a seven-point Likert-type scale (See Appendix B2). The affective states include the nine discrete adjectives that were reported as important affective states in driving contexts: fearful, happy, angry, depressed (sad), confused, embarrassed, urgent, bored, and relieved (M. Jeon & B. N. Walker, 2011).

Thereafter, the participants were given 12 minutes to write a description of a past emotional experience associated with anger. Participants in a neutral condition wrote mundane events of the day. For anger induced participants, the experimenter instructed the participants to remember the memory of the experience as clearly as possible and ask them to visit the experience emotionally again. As a reference, participants were shown two sample paragraphs, of which one is related to driving (See Appendix A). After this, the participants wrote down their experience. If there was more than one experience, they could choose to write about them within the time provided. If they complete the writing before 12 minutes, they were be instructed to re-read their own paragraph and encouraged to revisit that experience as vividly as possible.

After this, the participant filled out the emotional Likert scale again. Thereafter, the participant was asked to complete the driving task and fill out the emotional Likert scale again.

The participant was allowed to drive in the simulator and was required to react/respond to different multimodal displays (an auditory as well as visual display in the form of a virtual tablet on the screen showing the words "Takeover Control of the Vehicle" during takeover requests) in the vehicle in specific driving scenarios where drivers had to evade 3 obstacles, with the auditory warnings differing for each obstacle. The driving scenarios involved driving on a three-lane highway with 110 km/h (70 miles/h) speed limit. The visibility was lowered to approximately 100 meters using fog. The car began its journey on the automated driving system (ADS) on the middle lane of a three-lane highway. At randomly assigned times, the road had an obstacle presented to the participant, at which time, a takeover request was generated. Here the driver had to take over control of the vehicle using either the steering wheel or the brake pedal. No instructions were given to the participants on which method for takeover they could use, the participants were free to do as they thought fit. After avoiding the obstacle by switching lanes, participants were asked to hand over control to the vehicle by pulling on a lever present in the simulator setup. Each participant drove 3 laps of approximately 9 minutes each. Each lap consisted of 3 randomly assigned obstacles. In total, each participant experienced 9 different (3x3) warning sounds. After the completion all driving scenarios, the participant was asked to fill out the same emotional Likert type questionnaire.

Emotions are a temporary psychological state by definition. Therefore, the affective state that they self-induced during the experiment would not last longer than the overall experimental procedure. To this end, after the participants completed all the tasks, and rated their own emotional states and they were be debriefed and explained about the overall meaning of the experiment (see e.g. (Jeon, 2016; K. H. Kim, Bang, & Kim, 2004)). Thus, any potential emotional effects on their daily activities would be minimal.

4. ANALYSIS

All statistical analysis was performed using JMP Pro 15.0. To understand the differences of the effects of anger vs. neutral emotion, a descriptive analysis of the dependent measures was done. Depending on the normality of the residual distribution, parametric or non-parametric data analysis such as the Mann-Whitney U or Kruskal–Wallis test were conducted. For normally distributed residuals, ANOVA was used to analyze the data, when not, non-parametric analysis was used.

4.1 DEMOGRAPHICS

A total of 36 participants were recruited for this study. The participants were randomly selected groups into two groups: Anger induced and neutral drivers. Twenty-five participants were male and 11 were female. The mean age of the participants was 24.45 years with a standard deviation of 3.25 years. The median age was 24 years. On average, the participants had driving experience of 4.91 years.

4.2 EMOTION INDUCITON

Participant emotion manipulation checks were performed at three stages: At the start of the study, after induction and at the end of the driving scenario. There were no significant differences between anger levels at any point of the study for neutral drivers. There were significant differences in anger levels for angry drivers. A Kruskal-Wallis test resulted in $\chi^2(2) = 28.006$, $p < .0001$. A Wilcoxon each pair comparison showed after induction anger levels were higher than before induction $Z = 4.997$, $p < .0001$. Anger levels were significantly higher at the end of the study when compared to the start of the study $Z = 2.721$, $p = .0065$, implying the drivers stayed angry up until the end of the study.

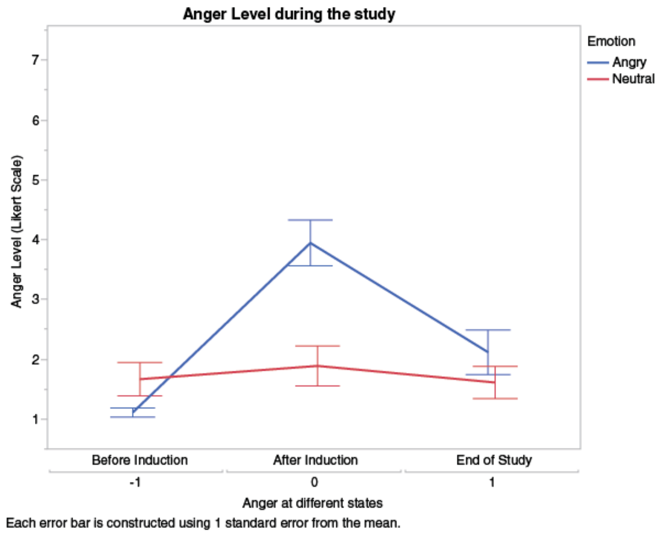


Figure 6: Anger level vs. Collection State. A comparison between Angry and Neutral drivers

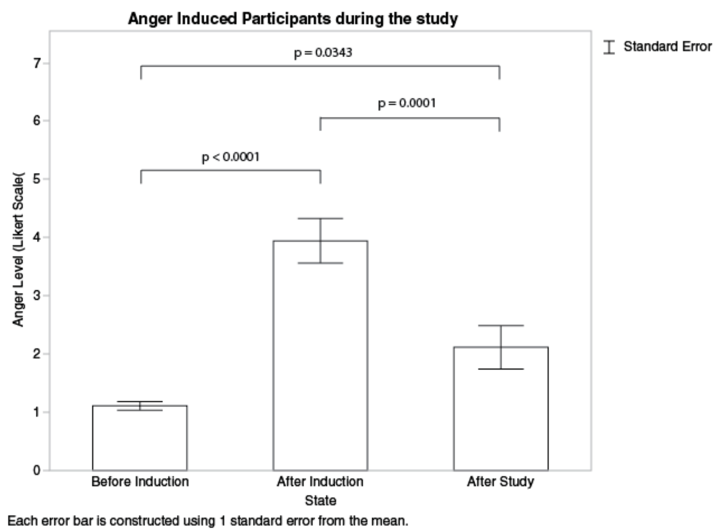


Figure 7: Anger levels in anger induced participants throughout the study.

4.3 TAKEOVER REACTION TIME

i. Reaction Time vs. Emotion Induced

Results were analyzed using a repeated-measures analysis of variance (ANOVA) for each level of affect, frequency, and number of repetitions per second. There was no main effect of induced affect to the reaction time: there were no significant differences between the reaction times for anger (M = 3.641s, SD = 0.923s) and neutral (M = 3.652s, SD =1.113s) drivers, F (1,33.73) = 0.0161, p = 0.899.

Table 3: Reaction times between angry and neutral drivers

	Reaction Time (ms)	
Emotion Induced	**Mean**	**Std Dev**
Angry	3641.0625	923.96710775
Neutral	3652.6573427	1113.6622437

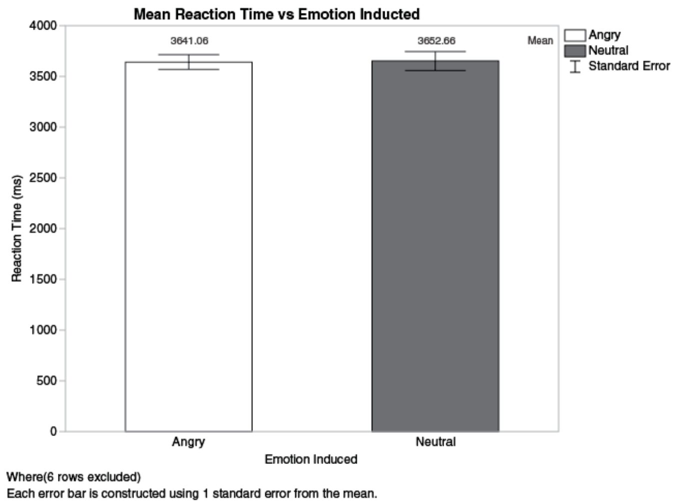


Figure 8: Mean reaction time vs. emotion induced.

ii. Reaction Time vs. Auditory Warnings

There was a downward trend for the reaction times for each auditory warning used. As shown below, as fundamental frequency increased and as number of repetitions increased, reaction times tended to be lower.

Table 4: Reaction Times vs. Frequency and Repetitions

Frequency	Number of Repetitions	Mean Reaction Time
F1	1	3917.1428
F1	4	3640
F1	8	3793.4285
F2	1	3712.580
F2	4	3425.882
F2	8	3712.647
F3	1	3627.5
F3	4	3537.575
F3	8	3435.454

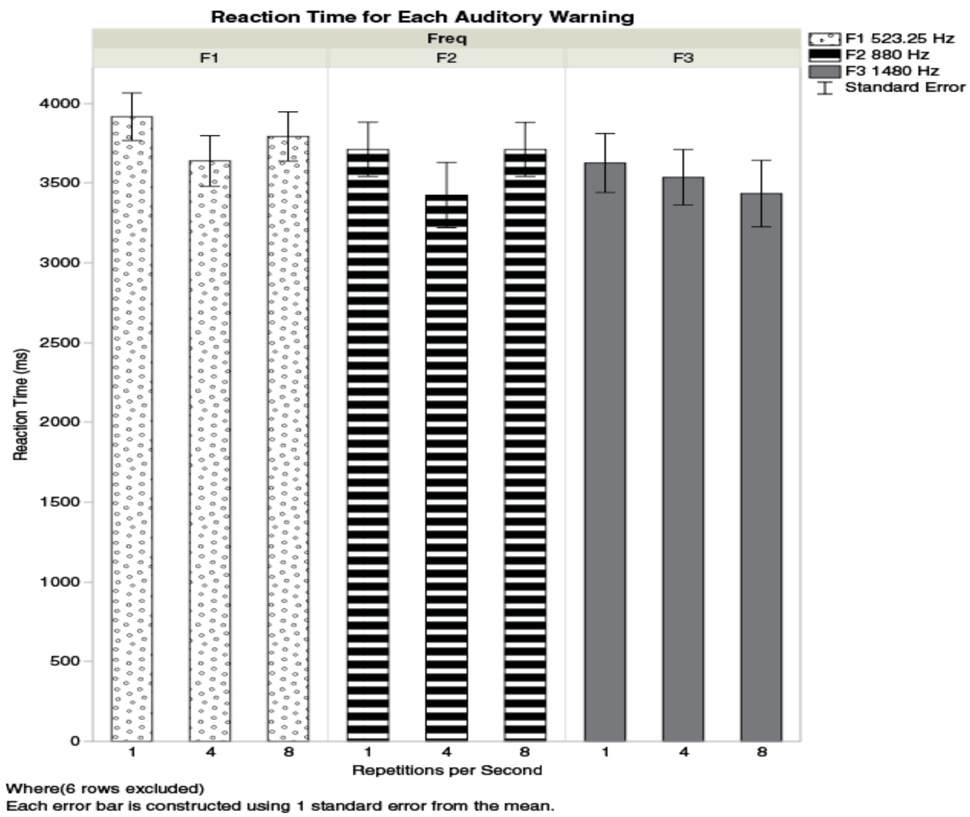


Figure 9: Sounds vs. Reaction Time

iii. Reaction Time vs. Frequency

There were significant differences in the reaction times for different levels of fundamental frequency (Fig. 3), F (2,251.5) = 4.736, p = 0.0096. F3(1480 HZ) led to a lower reaction time (M = 3.432s, SD = 1.07s) than F2(880 Hz) (M = 3.614s, SD = 1.04s) and F1(523.25 Hz) led to the longest reaction time (M = 3.782s, SD = 0.91s). For pairwise comparisons, a Bonferroni adjustment was applied to control for Type-I error, resulting in an adjusted alpha level (critical alpha level = 0.0167 (0.05/3)). Paired samples t-tests found that F3(1480 Hz) (M = 3.432s, SD = 1.107s) showed significantly lower reaction times than F1(523.25 Hz) (M = 3.782s, SD = 0.91s), t (257.63) = -3.092, p = 0.0022.

Table 5: Reaction Time vs. Fundamental Frequency

	Reaction Time (ms)	
Frequency	Mean	Std Dev
F1 (523.25 Hz)	3782.169	914.402
F2 (880 Hz)	3614.141	1049.201
F3 (1480 Hz)	3532.551	1078.676

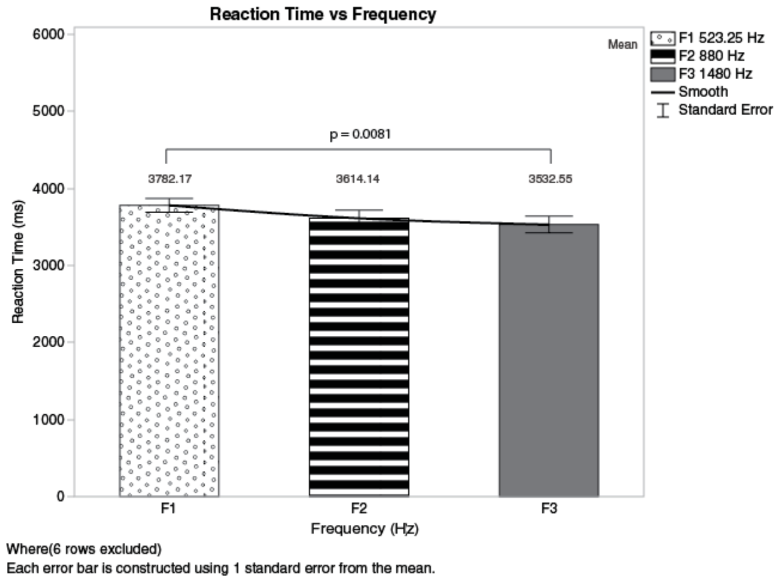


Figure 10: Reaction Times vs. Frequency

iv. Reaction Time vs. Repetitions

ANOVA results for takeover reaction times with respect to each number of repetition condition did not significantly differ for number of repetitions, F (2,256.9) = 2.579, p = 0.0778. However, planned analysis found that 4 repetitions per second (M = 3.536s, SD = 1.043s) showed lower reaction times than 1 per second (M = 3.757s, SD = .958s) and 8 repetitions per second (M = 3.650s, SD = 1.04s). A contrast between 1 & 8 repetitions versus 4 repetitions showed that 4 repetitions yielded significantly lower in reaction times F (1,256.8) = 4.328, p = 0.0385.

Table 6: Reaction times vs. Number of repetitions.

	Reaction Time (ms)	
Repetitions	**Mean**	**Std Dev**
1	3757.8571429	958.38916616
4	3536.5048544	1043.3812951
8	3650.6862745	1040.1116275

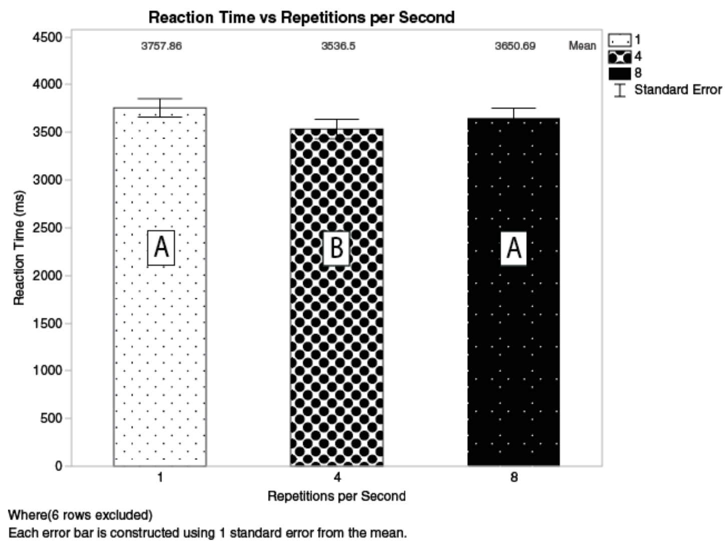


Figure 11: Reaction times vs. Number of repetitions per second. 1,8 represented by A, 4 represented by B.

4.4TAKEOVER QUALITY

4.4.1 NUMBER OF COLLISIONS (SUCCESS RATE)

There were only 4 collisions from a total of 324 takeovers conducted in the study. No significant differences were found between angry and neutral drivers.

Table 7: Number of collisions between angry and neutral drivers.

Emotion Induced	Number of Collisions
Angry	1
Neutral	3

4.4.2 REACTION TYPE

Angry drivers chose to brake more than neutral drivers more often $\chi^2(1) = 4.615$, $p = .0317$.

Table 8: Reaction Type between angry and neutral drivers

	Reaction Type	
Emotion Induced	Brake	Steering
Angry	41	116
Neutral	23	121

4.4.3 SPEED

Table 9: Driver Speed (min, average) vs. Emotion Induced

		Emotion Induced	
		Angry	**Neutral**
Average Speed	Mean	102.5478	98.9489
	Std Dev	7.76378	15.1424
Min Speed	Mean	93.3093	86.7785
	Std Dev	13.0155	27.3622

i. Minimum Speed vs. Emotion Induced

ANOVA results for minimum speed with respect to the two induced emotions showed that anger induced drivers (*M* = 93.3kmph, *SD* = 13.01kmph) had a significantly higher minimum speed compared to neutral induced drivers (*M* = 86.77kmph, *SD* = 27.36kmph), F (1,299) = 7.1754, p = 0.0078. The Welch test for unequal variances showed that neutral drivers had a higher variance in their minimum speeds, F (1,200.59) = 6.7936, p = 0.0098.

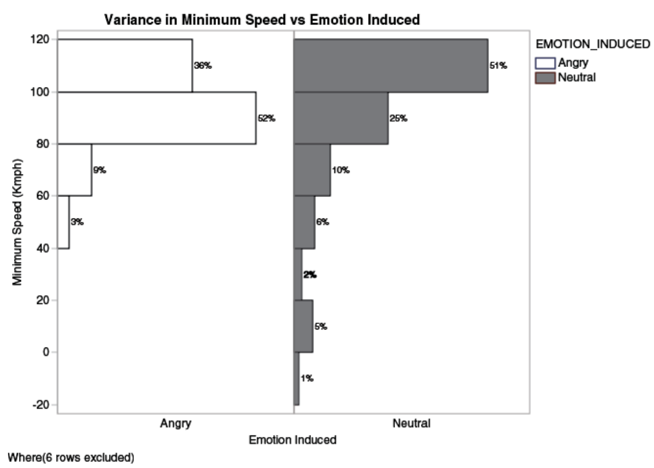


Figure 12: Variance in minimum speeds between angry and neutral drivers

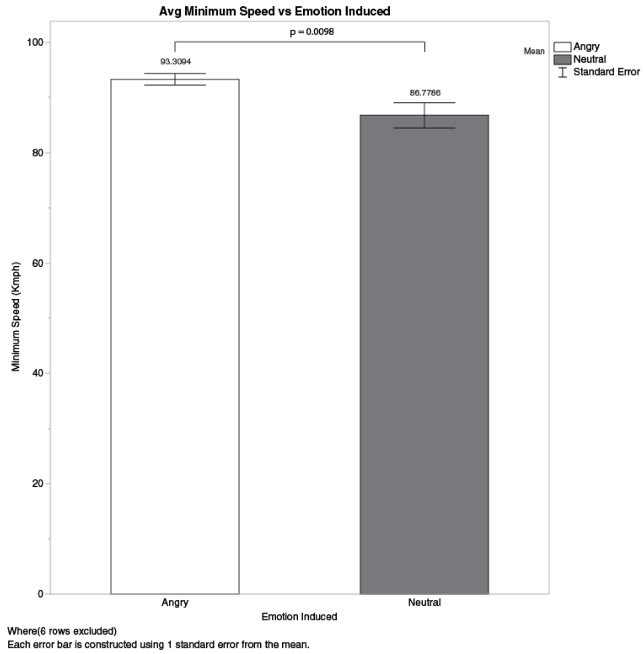


Figure 13: Minimum speeds between angry and neutral drivers

ii. Average Speed vs. Emotion Induced

ANOVA results for average speed with respect to the two induced emotions showed that anger induced drivers had a significantly higher average speed (*M* = 102.5kmph, *SD* = 7.76kmph) compared to neutral induced drivers (*M* = 98.94kmph, *SD* = 15.14kmph), *F* (1,299) = 6.8938, *p* = 0.0091. The Welch test for unequal variances showed that neutral drivers had a higher variance in their average speeds *F* (1,209.13) = 6.553, *p* = 0.0112.

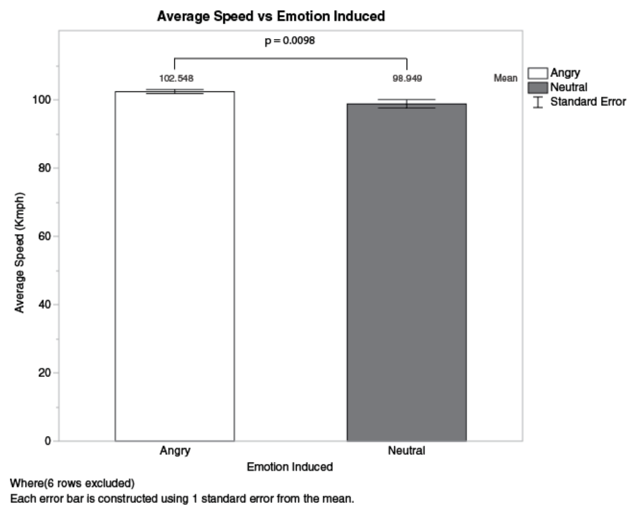


Figure 14: Variance in average speeds between angry and neutral drivers

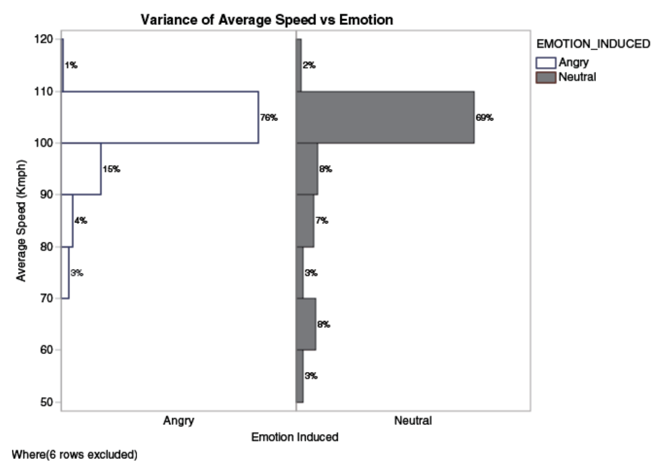


Figure 15: Average speeds between angry and neutral drivers

4.4.4 ACCELERATION/DECELERATION

Table 10: Acceleration (max, min) vs. Emotion Induced

		Emotion Induced	
		Angry	**Neutral**
Min Acceleration(m/s^2)	Mean	-2.3210	-2.3873
	Std Dev	2.6306	3.2437
Max Acceleration(m/s^2)	Mean	0.3735	0.8657
	Std Dev	0.6198	1.6634

6 rows have been excluded.

i. Maximum Deceleration vs. Emotion Induced

Neutral induced drivers (M = -2.38m/s^2, SD = 3.24m/s^2) had a numerically higher deceleration than angry drivers (M = -2.32m/s^2, SD = 2.63m/s^2), but it did not reach the conventional significance level.

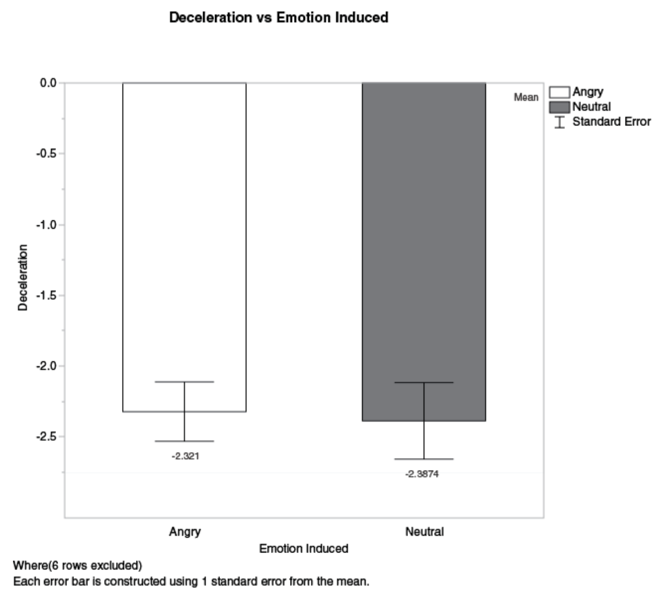


Figure 16: Deceleration vs. Emotion Induced

ii. Max Acceleration vs. Emotion Induced

There were significant differences in acceleration between neutral and anger induced drivers. The neutral induced drivers showed a higher acceleration (M = 0.865 $m/s2$, SD = 1.663 m/s^2) when compared to anger induced drivers (M = 0.37m/s^2, SD = 0.61$m/s2$), F (1,299) = 11.9395, p = 0.0006. The Welch test for unequal variances showed that neutral drivers had a higher variance in their maximum acceleration F (1,179.08) = 11.182, p = 0.001.

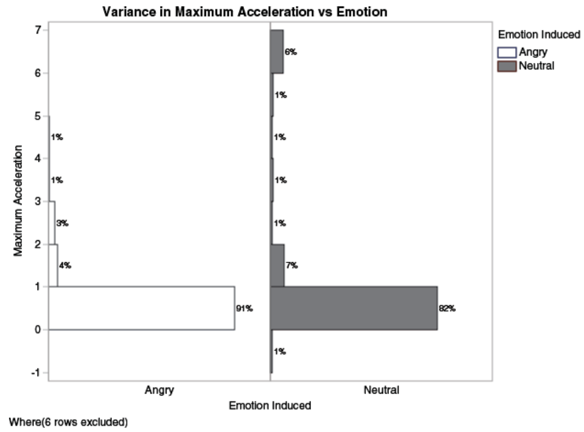


Figure 17: Variance in max acceleration vs. Emotion Induced

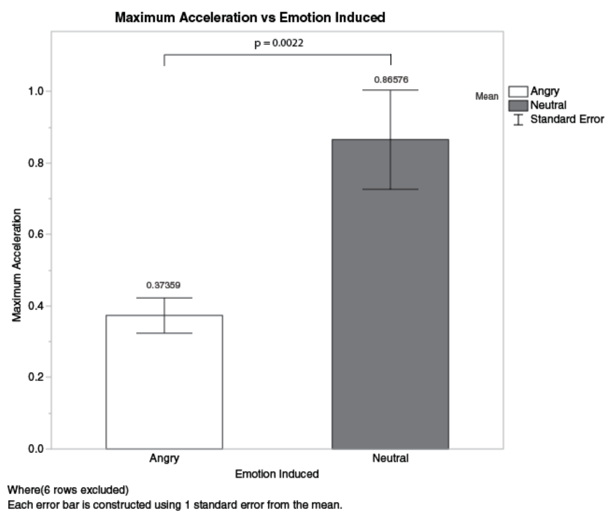


Figure 18: Acceleration vs. Emotion Induced

4.4.5 JERK

There were no significant differences between angry and neutral drivers for maximum and minimum jerk.

Table 11: Jerk (min, max) vs. Emotion Induced

		Emotion Induced	
		Angry	Neutral
Min Jerk ($m/s^2/s$)	Mean	-46.7318	-43.0149
	Std Dev	46.2465	44.8618
Max Jerk ($m/s^2/s$)	Mean	33.8171	38.8131
	Std Dev	33.4945	45.5718

i. **Max Jerk vs. Emotion Induced**

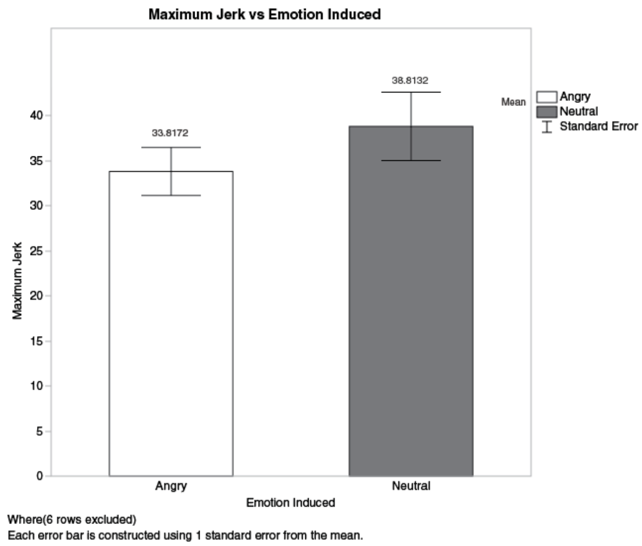


Figure 19: Minimum Jerk vs. Emotion Induced

ii. **Min Jerk vs. Emotion Induced**

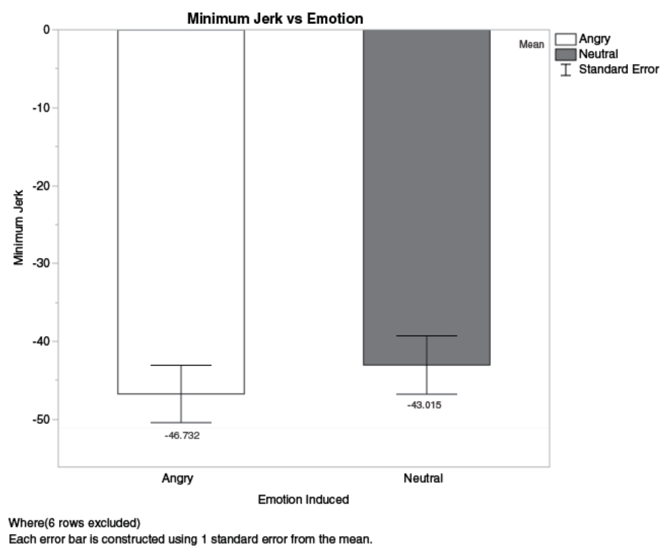


Figure 20: Maximum Jerk vs. Emotion Induced

4.4.6 STEERING WHEEL ANGLE

i. **Steering vs. Emotion Induced**

Neutral drivers had a higher max steering wheel angle, both left $\chi^2(1) = 8.779$, $p = .003$ and right $\chi^2(1) = 8.858$, $p = .0039$. Neutral drivers also had a higher variance for both maximum right and left steering wheel angles. Welch test for variance for left, $F\ (1{,}230.72) = 12.348$, $p = 0.0005$. Welch test for variance for right, $F\ (1{,}251.03) = 11.132$, p = 0.001.

Table 12: Steering wheel angles vs. Emotion Induced

		Emotion Induced	
		Angry	**Neutral**
Max Steering Left(degrees)	Mean	-16.5536	-20.1316
	Std Dev	6.3788	10.5817
Max Steering Right(degrees)	Mean	16.8962	20.2208
	Std Dev	6.8795	9.9840

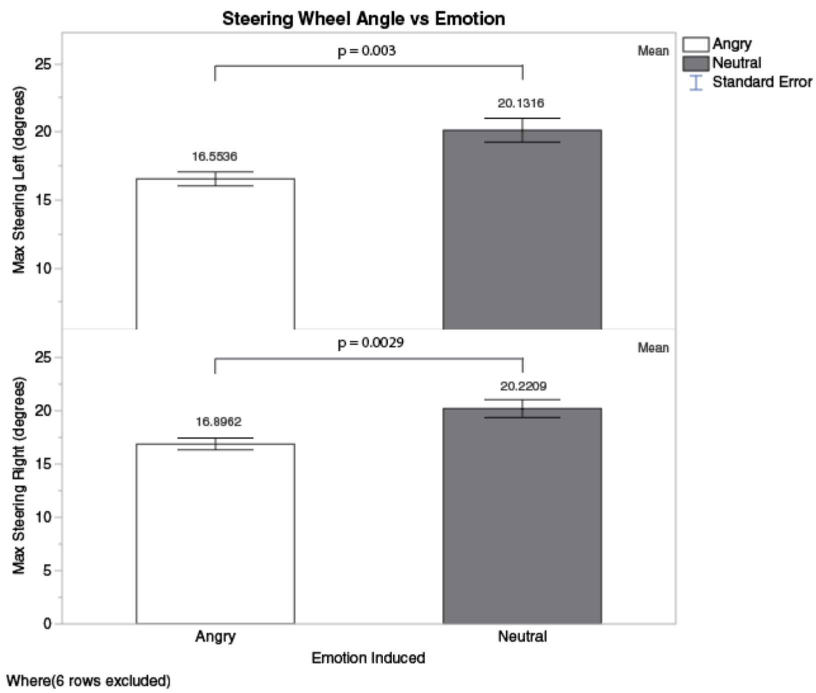


Figure 21: Steering Wheel angle vs. Emotion induced

4.4.7 LANE DEVIATIONS

There was no significant difference between the number of lane deviations for angry and neutral drivers. Angry drivers had a numerically higher number of deviations.

Emotion Induced	Number of Lane Deviations
Angry	156
Neutral	143

4.4.8 LANE CHANGE DURATION

The majority of the outliers came from three neutral drivers, after removing them, there was found to be significant differences between the lane change duration of angry and neutral drivers, with angry drivers taking longer to change lanes $\chi^2(1) = 8.832$, $p = .003$.

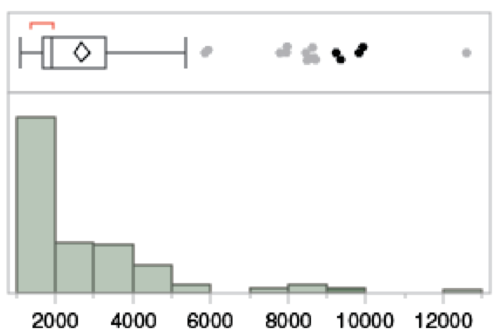


Figure 22: Distribution of lane change durations(milliseconds) showing outliers.3 Outlier participants were removed.

Table 13: Lane Change Durations vs. Emotion Induced

	Lane Change Duration (ms)	
Emotion Induced	Mean	Std Dev
Angry	2381.8064	903.6832
Neutral	2235.4621	1090.6262W

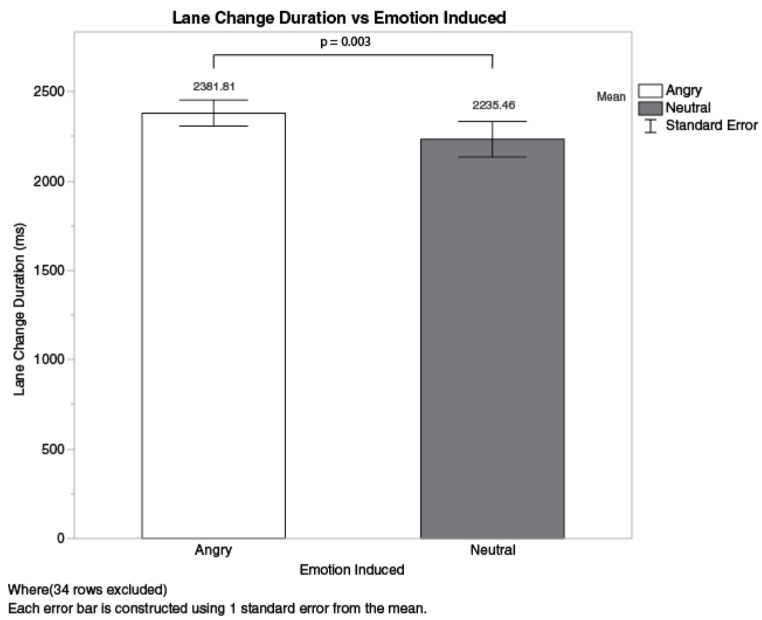


Figure 23: Lane Change Duration vs. Emotion Induced

4.5 SUMMARY OF TAKEOVER PERFORMANCE

4.5.1 EMOTION MANIPULATION

Emotion induction was successful for angry drivers and the drivers remained significantly angry by the end of the study. Neutral drivers did not show significant differences in their anger levels throughout the duration of the study.

4.5.2 TAKEOVER REACTION TIME

i. Reaction Time

Emotion did not have a significant effect on takeover time, but frequency did have a significant effect on takeover time, with a higher frequency corresponding with shorter reaction times. 1 and 8 repetitions showed higher reaction times compared to 4 repetitions, this could likely be because 4 was more salient than 1 or 8.

4.5.3 TAKEOVER QUALITY

i. Speed

Angry drivers had higher minimum and averages speeds than neutral drivers. Neutral drivers also had higher variances in minimum and average speeds.

ii. **Acceleration & Deceleration**

Neutral drivers showed higher acceleration and a higher variance in acceleration. Deceleration was higher for neutral drivers, but not statistically significant.

iii. **Jerk**

There were no significant differences in jerk between angry and neutral drivers.

iv. **Steering Wheel Angle**

Neutral drivers had higher steering wheel angles and variances when compared to neutral drivers.

v. **Lane Change Duration**

Angry drivers took longer to change lanes when compared to neutral drivers.

vi. **Lane Departures**

Angry drivers had higher lane departures but not significantly so.

ii. **Reaction Type**

Angry drivers used braking more for takeover when compared to neutral drivers.

iii. **Takeover Success Rate (Collisions)**

No significant differences between angry and neutral drivers in terms of collisions.

4.6 EYE TRACKING ANALYSIS

4.6.1 AREAS OF INTEREST

Below are the Areas of Interest that were defined for the analysis: Side View Mirrors, Rearview Mirrors, Current Lane (Middle), Changing Lane (Right or Left Lane), Tablet and TOR Display.

Figure 24: Areas of Interest: Side View Mirrors, Rearview Mirrors, Current Lane (Middle), Changing Lane (Right or Left Lane), Tablet and TOR Display

4.6.2 ANALYSIS

Out of 324 TOR scenarios, eye tracking data for 207 TOR scenarios were acceptable, i.e. the eye tracking data had enough gaze samples for analysis. 96 from angry drivers, 111 from neutral drivers. There were no significant differences between the number of gazes on the current lane, changing lane, side mirrors and rearview mirrors between angry and neutral drivers.

i. Number of Gazes vs. Emotion Induced (All Data)

Table 14:The total number of gazes on the current lane vs. changing lane

	Current Lane	Changing Lane
Emotion	**Sum**	**Sum**
Angry	535	141
Neutral	438	120

Table 15:The total number of gazes on the Side Mirrors and Rearview Mirrors

	Side Mirrors	Rearview
Emotion	**Sum**	**Sum**
Angry	9	14
Neutral	8	10

ii. Average Gaze Duration vs. Emotion Induced (All Data)

A two-sample t-test found that average gaze duration on the current lane was higher for neutral drivers t (170.157) = 2.0451, p = 0.0424. A two-sample t-test found that average gaze duration on the changing lane was higher for neutral drivers t (96.259) = 2.772, p = 0.0067.

Table 16:Average Gaze Duration on Current Lane vs. Changing Lane

	Average Gaze duration on Current Lane		Average Gaze duration on Changing Lane	
Emotion	**Mean**	**Std Dev**	**Mean**	**Std Dev**
Angry	837.989	738.618	952.758	1096.665
Neutral	1148.037	1357.143	1754.154	2040.754

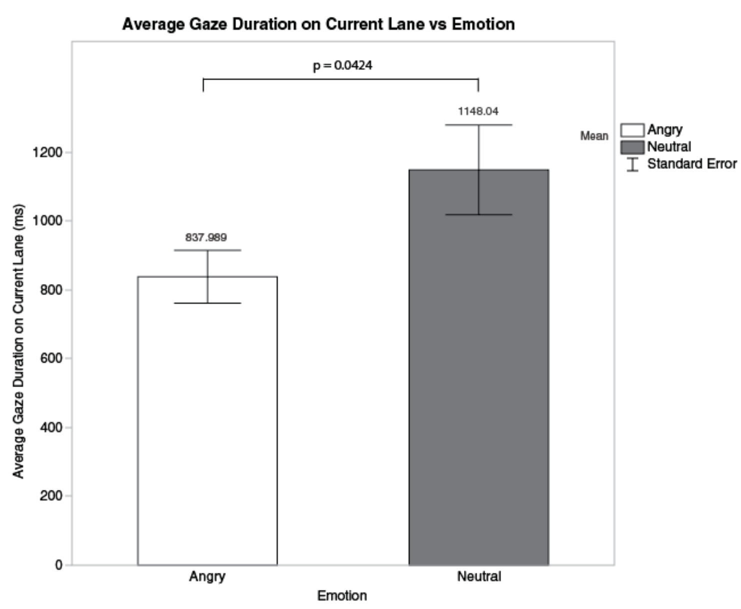


Figure 25: Average Gaze Duration on Current Lane vs. Emotion (All Data)

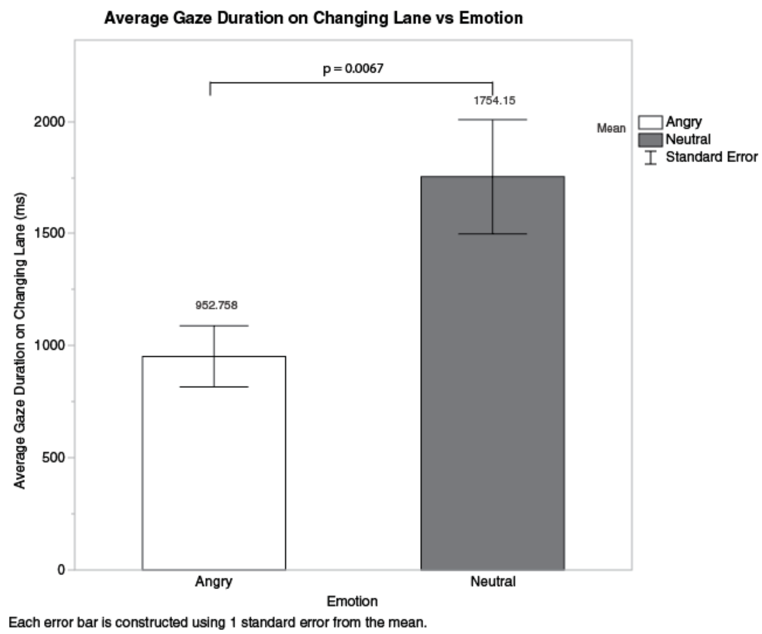


Figure 26: Average Gaze Duration on Changing Lane vs. Emotion (All Data)

There were no significant differences between average gaze durations on the rearview or side mirrors between angry and neutral drivers.

Table 17: Average Gaze Duration on Side and Rearview Mirrors

	Average Gaze duration on Side Mirrors (ms)		**Average Gaze duration on Rearview Mirror (ms)**	
Emotion	**Mean**	**Std Dev**	**Mean**	**Std Dev**
Angry	160.952	46.256	243.888	186.845
Neutral	251.428	145.994	256.666	182.345

4.6.3 ANALYSIS: PARTICIPANTS WHO GAZED AT MIRRORS

Looking further into the data, only 30 instances of mirror use were found out of 207 takeover requests. 15 were for angry drivers and 15 for neutral drivers. Below is the analysis of data for these 30 data points.

Table 18: Number of participants divided according usage of mirrors

	Participants who used mirrors	
Emotion	**Used Mirrors**	**No Mirrors**
Angry	15	81
Neutral	15	96

i. Number of Glances vs. Emotion Induced (Mirror Users)

There were no significant differences between angry and neutral drivers in terms of number of glances on rearview mirrors, side mirrors, current lane and changing lanes.

Table 19: Number of Glances on Current Lane vs. Changing Lane

	Current Lane	**Changing Lane**
Emotion	**Sum**	**Sum**
Angry	103	30
Neutral	100	11

Table 20: Number of Glances on Side and Rearview Mirrors

	Side Mirrors	**Rearview**
Emotion	**Sum**	**Sum**
Angry	9	14
Neutral	8	10

ii. Average Glance Duration vs. Emotion Induced (Mirror Users)

No significant differences were found for average gaze duration on current or changing lanes between angry and neutral drivers.

Table 21: Average Gaze Duration on the Current Lane and Changing Lanes (ms)

	Current Lane (ms)		**Changing Lane (ms)**	
Emotion	**Mean**	**Std Dev**	**Mean**	**Std Dev**
Angry	575.423	610.432	917.228	1108.05
Neutral	459.505	266.7067	684	926.327

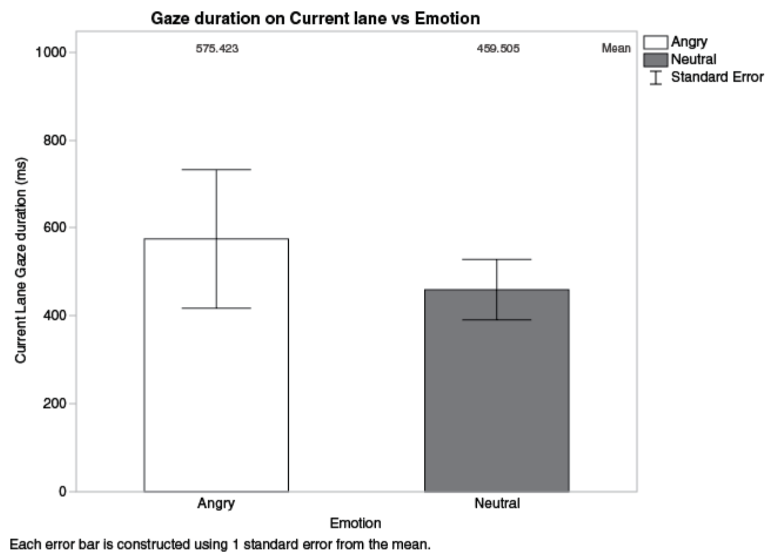


Figure 27: Gaze Duration on Current Lane vs. Emotion Induced

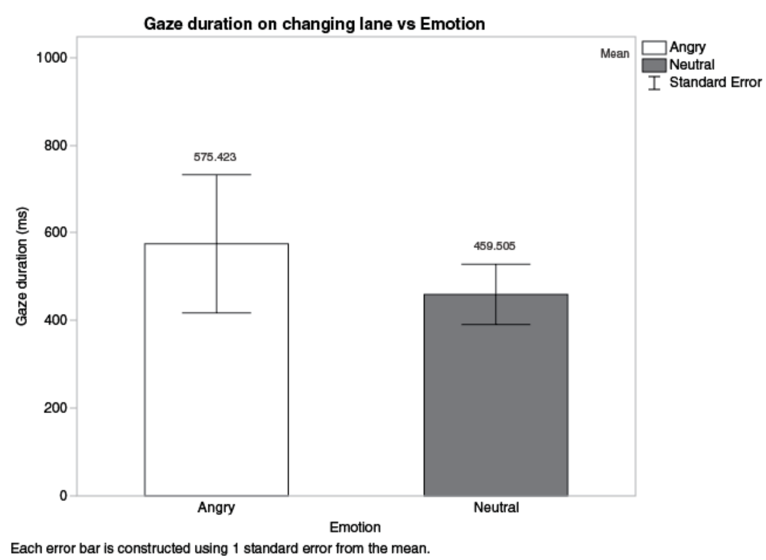


Figure 28: Gaze Duration on Changing Lane vs. Emotion Induced

No significant differences were found for average gaze duration on side or rearview mirrors between angry and neutral drivers.

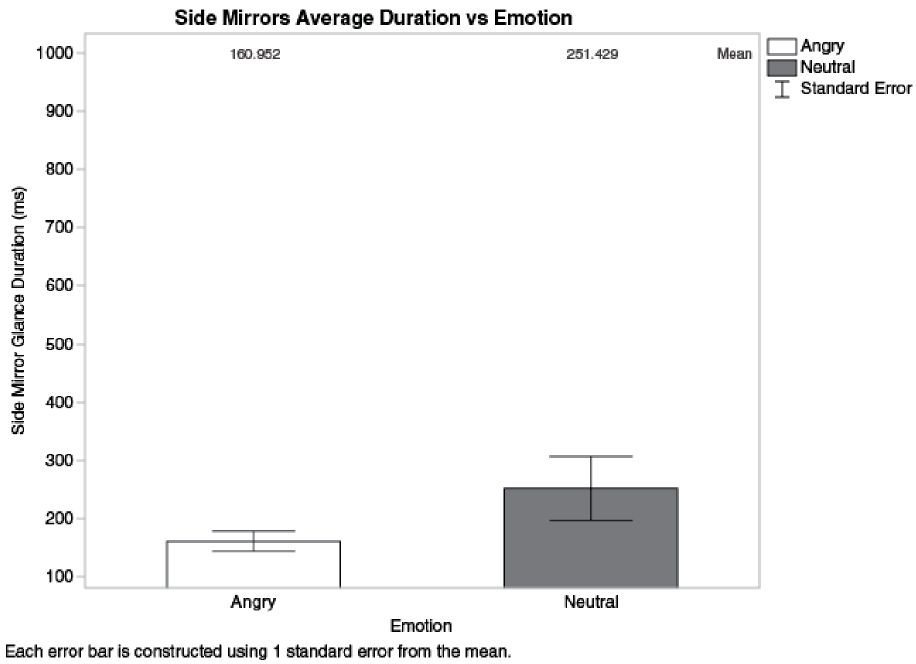


Figure 29: Average Gaze Duration on Side Mirrors vs. Emotion

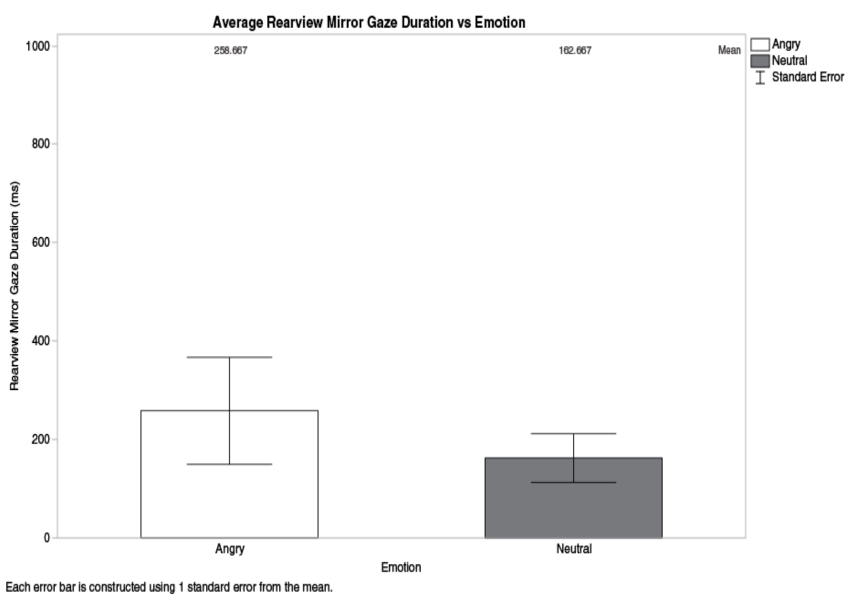


Figure 30: Average Gaze Duration on Rearview Mirror vs. Emotion Induced

iii. Average Glance Duration Percentage vs. Emotion Induced (Mirror Users)

No significant differences were found for average gaze duration percentage (as a percentage of the whole duration of takeover) on current or changing lanes between angry and neutral drivers.

Table 22: Gaze Duration Percentage for Current and Switching Lanes

	Current Lane		Changing Lane	
Emotion	**Mean**	**Std Dev**	**Mean**	**Std Dev**
Angry	56.8%	27.6%	19.6%	23.8%
Neutral	62.5%	26.2%	9.4%	21.1%

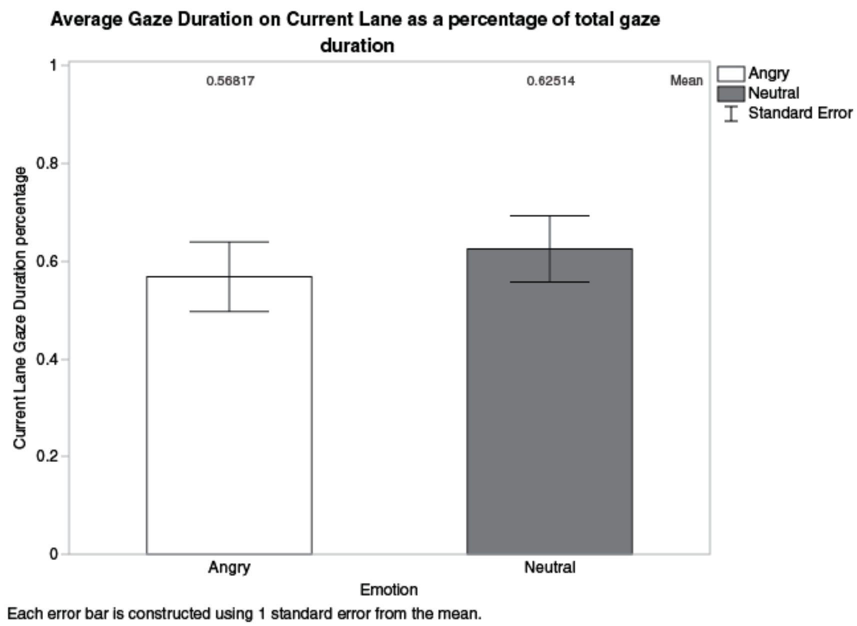


Figure 31: Average Gaze Duration on Current Lane as a percentage of total gaze Duration

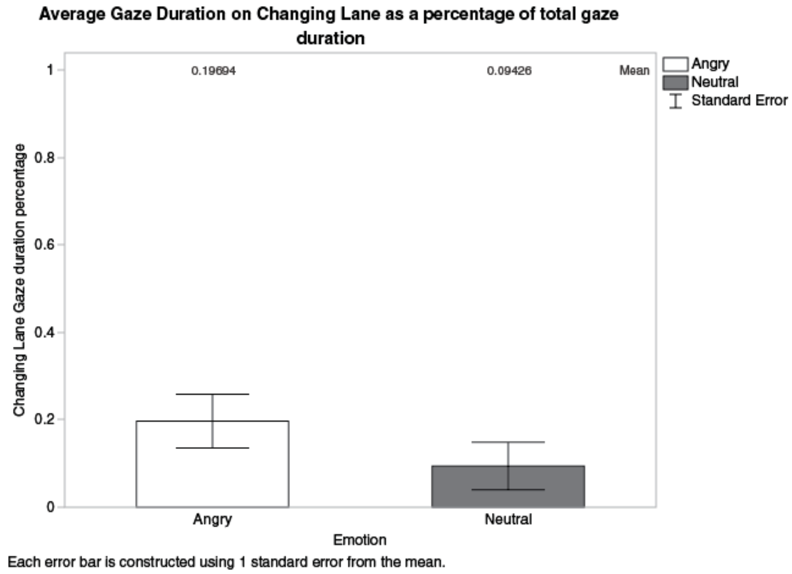


Figure 32: Average Gaze Duration on Changing Lane as a percentage of total gaze Duration

Table 23: Gaze Duration Percentage on Side Mirrors and Rearview Mirrors

	Side Mirror %		**Rearview %**	
Emotion	**Mean**	**Std Dev**	**Mean**	**Std Dev**
Angry	2.02%	2.9%	7.09%	14.1%
Neutral	7.06%	13.1%	2.6%	2.8%

No significant differences were found for average gaze duration percentage (as a percentage of the entire duration of takeover) on side and rearview mirrors between angry and neutral drivers.

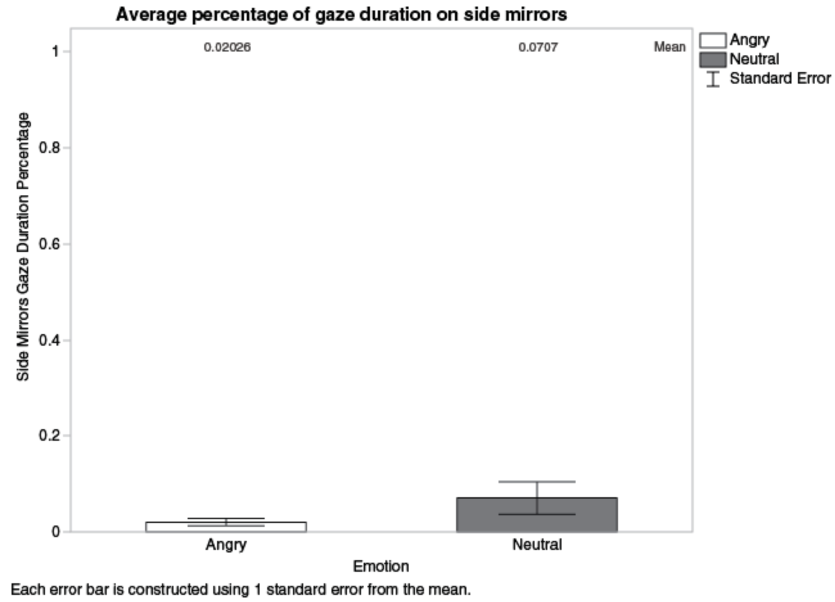


Figure 33: Average Gaze Duration on Side Mirrors as a percentage of Total Gaze Duration

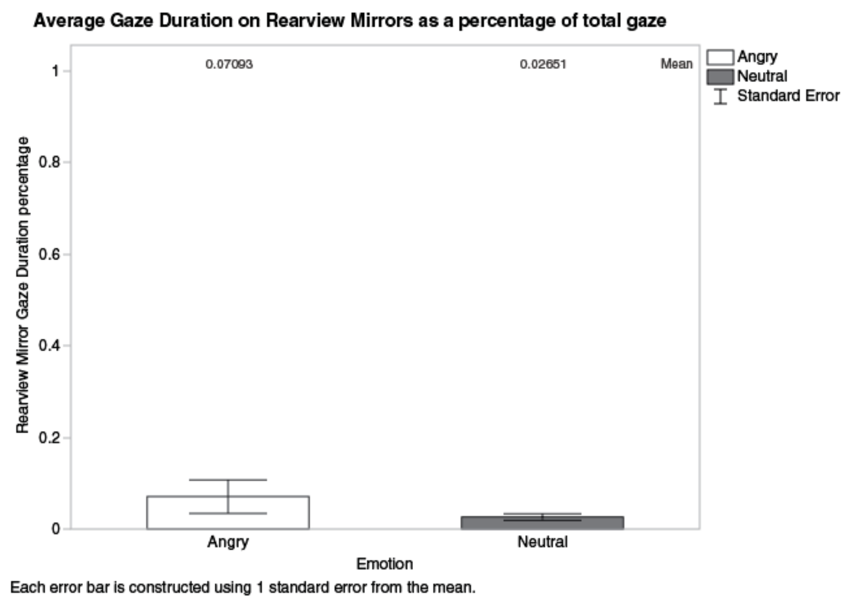


Figure 34: Average Gaze Duration on Rearview Mirror as a percentage of Total Gaze

4.6.4 SUMMARY OF EYE TRACKING ANALYSIS RESULTS

To summarize, an overall comparison of the angry and neutral drivers found that were very few instances where drivers used the rearview or side mirrors for lane change. Instead Many drivers used visual resources to view changing lane when switching lanes and mainly used the current lane for driving purposes. The heat map of both angry and neutral drivers showed similar patterns and weights.

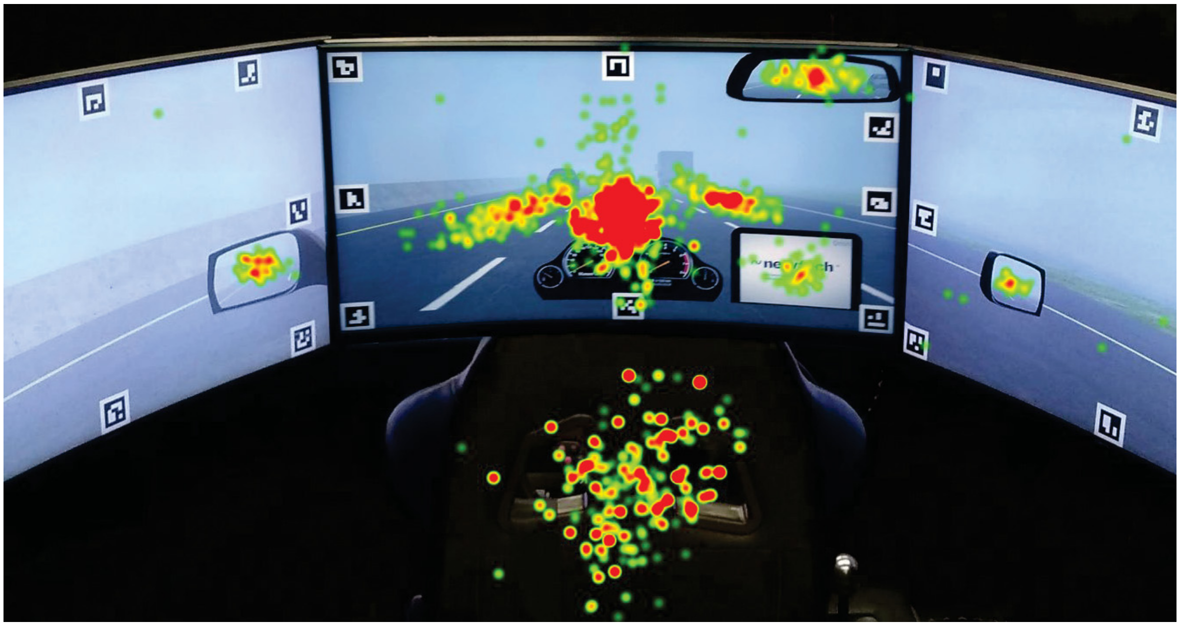


Figure 36: Heat Map of Angry Drivers Gaze during the Takeover Task

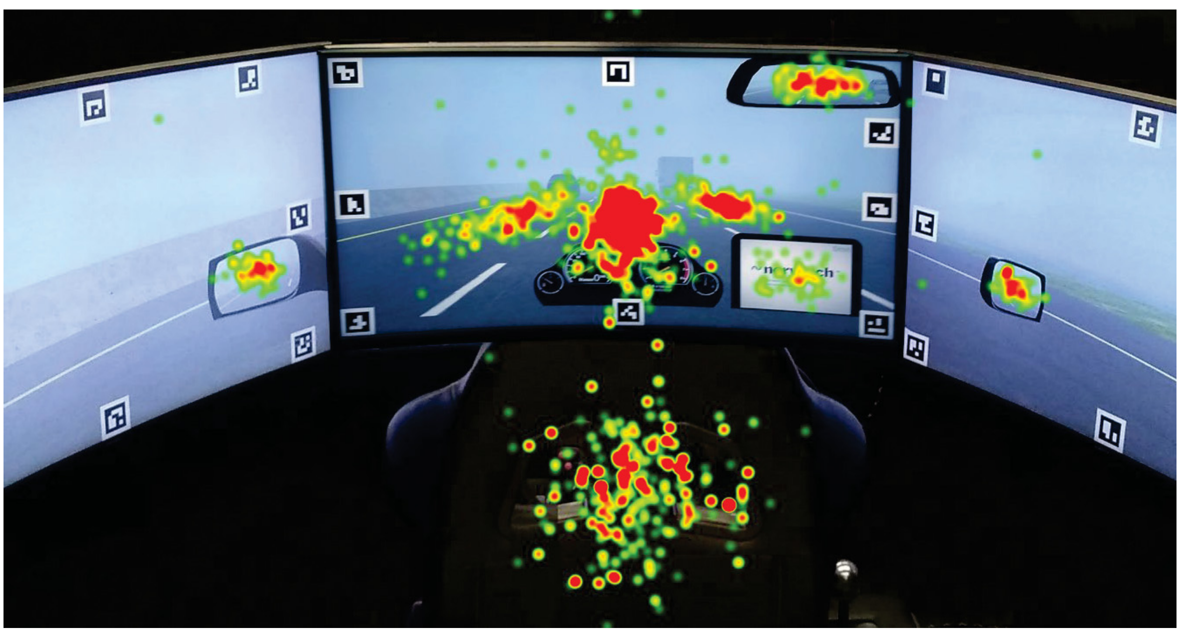


Figure 35: Heat Map of Neutral Drivers Gaze during the Takeover Task

Additionally, angry drivers had lower average gaze durations on the current lane as well as the switching lanes when compared to neutral drivers. As seen in the data analysis, angry drivers drove faster than neutral drivers, which could explain the shorter duration as the angry drivers spent less time on the takeover lane change. This also reflects in the average of the total duration of the gaze samples collected. Angry drivers on average spent less time for takeover drives when compared to neutral drivers.

Table 24: Mean of Total Gaze Duration from all Gaze samples collected

Total Gaze Duration from all Gaze Samples Collected per Driver	
Emotion	**Mean (ms)**
Angry	5712.270
Neutral	6552.531

Of the 30 instances of drivers who used the rearview or side mirrors, the instances were equally divided into 15 angry and 15 neutral drivers. There were no significant differences between angry drivers in terms of number of glances, average gaze durations, percentage of total gaze duration for the following: Side mirrors, rearview mirrors, changing lanes and current lanes. This suggests that this behavior is more related to driver behavior than differences related to emotion.

Additionally, the low number of instances were drivers who used the mirrors may be because of the fact that the simulator may have led participants to behave different when it came to safety.

In conclusion, eye tracking data did not show any significant indications of unsafe driving by angry drivers, but did conform with the fact that angry drivers drove faster.

4.7 QN-MHP MODELLING RESULTS

4.7.1 USING THE QN-MHP MODEL TO PREDICT REACTION TIMES

The reaction time was measured using P_{WU} (Warning Urgency), P_{HU} (Hazard Urgency) and P_{TR} (Perceived Trust). The warning urgency was calculated using loudness (70 dBA), semantics (1) and warning acoustic characteristics.

$$P_{WU}(i, j, wl, wsm) = \frac{1}{2}\left(U(wl) + U(wsm) + U(wac)\right)$$

Fundamental frequency and number of repetitions were varied while pitch range was kept constant at 7 semi-tones. Using the below equation, the urgency for warning acoustic characteristics were calculated.

$$U(wac) = \frac{1}{3}\left(U(wfreq) + U(wrep) + U(wpit)\right)$$

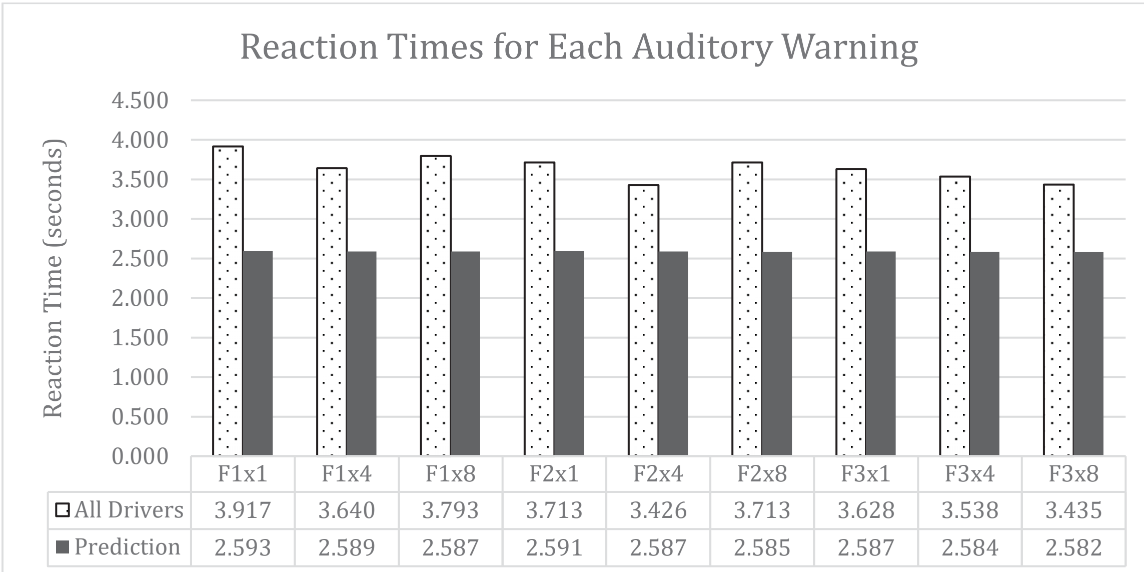
Where *U(wfreq)* is the urgency for fundamental frequency, *U(wrep)* is the urgency for the number of the repetitions per second, and *U(wpit)* is the urgency for the pitch range of dominant frequencies (Ko et al., 2019).

$$U(wfreq) = \left(0.0255 \times F_{fundamental}\right) + 61.8383$$
$$U(wrep) = \left(30.2295 \times N_{repetitions\ per\ second}\right) + 45$$
$$U(wpit) = \left(1.8553 \times D_{pitch}\right) + 42.6053$$

4.7.2 VALIDATION OF MODELLING RESULTS

i. Reaction Times for Each Auditory Warning

From the data analysis above, it was found that there were no significant differences in the reaction time between neutral drivers and angry drivers. Therefore, the modelled reaction times were analyzed against the overall reaction time data collected from the empirical study. The model predictions and the validation data are shown in the figure below. The verification of the model was conducted via the Pearson correlation coefficient (R-squared). The R-square value for the model was 0.49 for all drivers combined.

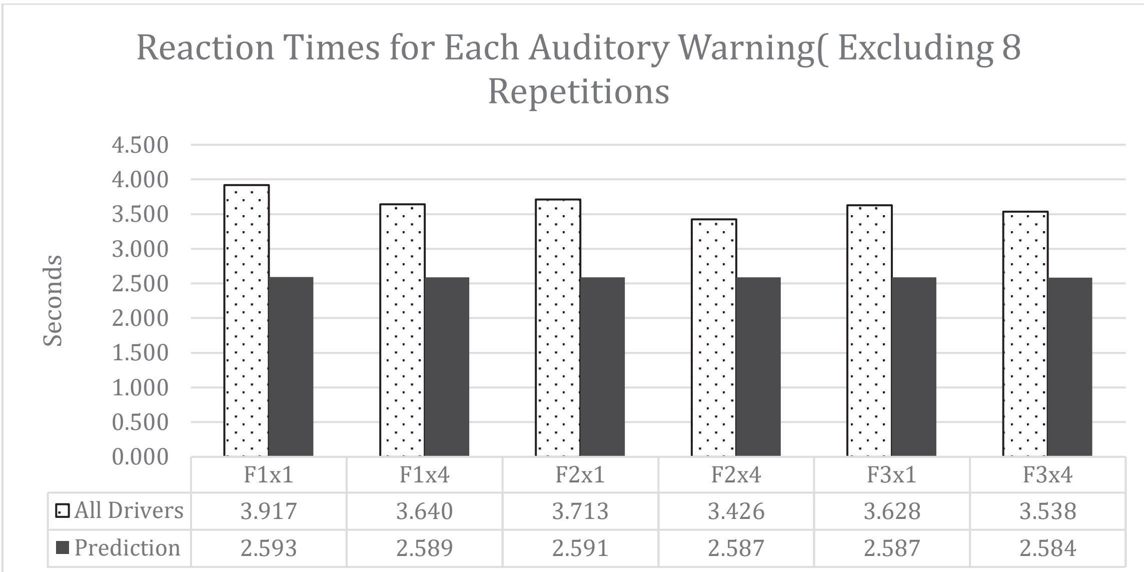


R^2 values for Empirical Data vs. Predicted data	
Drivers	**R^2**
All Drivers	0.4997

ii. Reaction Times without 8 repetitions per second included

A higher number of repetitions in auditory warnings would result in higher perceived urgency and therefore faster reaction times. This increase in perceived urgency due the increase in the number of repetitions per second was incorporated into the model as well.

However, analysis from the empirical data showed that although an increase of 1 repetition per second to 4 repetitions per second resulted in faster reaction times, the increase to 8 repetitions per second did not show a reduction in reaction time. Thus, the low correlation of the data with the modelled predictions was due to the fact the reaction time for the 8 repetitions auditory warnings did not show a reduction as the model would predict it be. After removing reaction times for 8 repetitions per second for the correlation analysis the R^2 improved significantly. The model predictions and the validation data are shown in the figure below. The verification of the model was conducted via the Pearson correlation coefficient (R-squared). The R-square values for the model was 0.68 for all drivers combined.



R^2 values for Empirical Data vs. Predicted data	
Drivers	**R^2**
All Drivers	0.6892

5. DISCUSSION

5.1 REVISITING THE GOALS

The primary goal of this study was to measure how anger would influence driver performance and safety for takeover requests in level 3 automated vehicles. The secondary goal of this study was to test and compare the QN-MHP model's predictions of takeover reaction times with those from the empirically collected data. To help reach these goals, two research questions were formulated with corresponding hypotheses.

R1: Does anger have an adverse effect on takeover reaction time in level 3 automated vehicles?

Hypothesis 1 (H1): Reaction time for takeover requests will be longer for participants with induced anger

Hypothesis 2 (H2): The modelled reaction time for takeover requests will be significantly different from the reaction time for angry drivers

R2: Does anger have an adverse effect on lane change safety in level 3 automated vehicles upon a takeover request?

Hypothesis 3 (H3): Lane change duration will be significantly less for angry drivers

Hypothesis 4 (H4): Lane departures will be significantly more for angry drivers

Hypothesis 5 (H5): Glance frequency and duration on the vehicle mirrors will be less for angry drivers as compared to neutral drivers

Additionally, it is expected that perceived urgency for the auditory warning would change based on auditory characterizes: **Hypothesis 6 (H6):** Urgent Auditory alerts with higher pitch range and higher repetitions will show faster takeover reaction time

5.2 EMOTION INDUCTION

To understand how anger would influence driving performance, it is important to verify the emotion manipulation performed during the study. The results of this study suggest that the emotion induction was successful for angry drivers and the drivers remained significantly angry by the end of the study. This was as expected and reflected previous studies that used autobiographical recall methodology to make drivers angry (Jeon, 2016; Jeon, Walker, &

Gable, 2014; Jeon et al., 2011). Neutral drivers did not show significant differences in their anger levels throughout the duration of the study, which was also expected.

5.3TAKEOVER REACTION TIME

To answer the first research question **R1**: "Does anger have an adverse effect on takeover reaction time in level 3 automated vehicles?", three dependent measures were chosen. Namely, takeover reaction time, reaction type and success rate (number of collisions).

Angry drivers took on average 3.64 seconds while neutral drivers took on average 3.65 seconds for takeover. This reaction time is slightly higher than other similar studies (Kutchek & Jeon, 2019). This maybe because of the switching costs associated with leaving the NDRT to take over control of the vehicle (Zeeb, Härtel, Buchner, & Schrauf, 2017).

The data collected suggest that anger did not have a significant effect on the takeover reaction time. This is in direct opposition to **H1**: "Reaction time for takeover requests will be longer for participants with induced anger". Therefore, H1 was not supported by the results of the study. Previous research has shown that angry drivers perform worse in the driving context as perception, focus and attention can be compromised (Deffenbacher, Oetting, & Lynch, 1994; Eyben et al., 2010). In this study since takeover requests are an emergent condition with times measuring only a few short seconds, it may be that the arousal generated from the takeover request may be enough for drivers to react to an auditory warning. Higher arousal has been shown to improve response time in a dual-task setting, if we consider the takeover as the switching between the NDRT and the driving task (Zwosta, Hommel, Goschke, & Fischer, 2013). Therefore, it makes sense that even though anger is a negative valence emotion, reaction times are not necessarily going to be affected.

It has also been advised by NHSTA that auditory warnings in semi-automated vehicles should have higher perceived urgency to improve reaction times(Campbell et al., 2018). This could be facilitated by increasing the number of repetitions per second of the warning or by increasing the fundamental frequency of a warning. The results of this study correspond with the NHSTA guidelines in the fact that higher frequency warnings lead to faster reaction times.

This can be seen in the trend of decreasing reaction times. F1, 523.25 Hz lead to a reaction time of 3.782 seconds (SD = .91s), F2, 880 Hz lead to a reaction time of 3.614 seconds (SD = .104s) and finally F3, 1480 Hz lead to a reaction time of 3.532 seconds (SD = .107s), with F3 being significantly lower than F1.

The number of repetitions did not have significant differences between each other but seen numerically, 1 repetition per second had higher reaction times (M = 3.757s, SD = .958s) than 4 repetitions per second (M = 3.536s, SD = 1.043s). This does follow the pattern that a higher number of repetitions leads to faster reaction times as suggested by NHSTA (Campbell et al., 2018), but not definitively so. Meanwhile, 8 repetitions per second was lower than 1 repetition per second but in fact higher than 4 repetitions per second in terms of reaction time (M = 3.65s, SD = 1.04s). A further contrast showed that 1 and 8 repetitions per second when taken as a group have a significantly higher reaction time when compared to 4 repetitions per second. This may be because of the fact that 4 repetitions per second was more salient from 1 and 8 repetitions per second. As I did not collect post study, subjective questionnaires on participants' perception of these sounds, it cannot definitively be associated with a difference in saliency. Hellier et al. (1993) showed that fundamental frequency contributed more than repetition levels to perceived urgency levels. This may also be why we are seeing a more pronounced effect of fundamental frequency on reaction time when compared with the number of repetitions.

This could be the subject of future studies to compare the effect of repetitions per second in auditory alerts to see if there is a ceiling after which saliency reduces. As a result, **H6:** "Urgent Auditory alerts with higher pitch range and higher repetitions will show faster takeover reaction time" was only partially supported.

In terms of reaction type, angry drivers used brake more often when compared to neutral drivers, but the primary method for takeover for most drivers was steering. Additionally, out of a total of 324 takeover requests faced by participants only 4 resulted in collisions. This could likely be because the appropriate length of lead time (7s) given to the participant before the impending obstacles (Damböck & Bengler, 2012; Gold et al., 2015; McDonald et al., 2019).

5.4 TAKEOVER QUALITY

To answer the first research question **R2**: "Does anger have an adverse effect on lane change safety in level 3 automated vehicles upon a takeover request?", lane departures, lane change duration and glance frequency on vehicle mirrors were used(Bueno et al.; Radlmayr et al., 2014; Zeeb et al., 2015). Additionally, speed, acceleration/deceleration, steering wheel angle and jerk were used to measure the quality of the takeover.

To better understand how this study answers **R2**, it is worth discussing speed, acceleration and jerk as these parameters describe driver behaviors that affect lane departures and lane change duration. In terms of speed after the takeover, angry drivers had higher minimum and average speeds than neutral drivers. Neutral drivers had higher variances in both minimum and average speeds. This indicates that neutral drivers slowed down more often when compared to angry drivers. The higher speeds for angry drivers also correspond to previous research findings on angry driving (Deffenbacher, Filetti, Lynch, Dahlen, & Oetting, 2002; Stephens & Groeger, 2009).

Additionally, neutral drivers had a numerically higher deceleration and a significantly higher acceleration when compared to angry drivers. Neutral drivers also had a higher variance in acceleration compared to angry drivers. This finding further builds on the idea that neutral drivers slowed down more after takeover with the higher deceleration, lower minimum and average speeds and the fact that they accelerated more indicates the requirement to reach the speed limit after slowing down.

When braking suddenly or during collisions, vehicle passengers (in this case our participants) whip forward with an initial acceleration that is larger than during the rest of the braking process, which can cause whiplash. This can be characterized as jerk, that is the change in acceleration per second. A high jerk value can indicate how dangerous a braking action was (Bahram, Aeberhard, & Wollherr, 2015). In terms of jerk, both maximum and minimum jerk values did not indicate any significant differences between angry and neutral drivers. This could most likely be again due to the appropriate lead time of 7 seconds provided to participants, which allowed them to takeover the vehicle with a reduced risk of collision.

The maximum steering wheel angle was calculated for both left and right turns in the study. Neutral drivers had significantly higher steering wheel angles compared to angry drivers. This could be indicative of the fact that a slower speed of driving would require higher steering angles to complete a turn. Additionally, it could also be indicative of a better evasion of obstacle by neutral drivers.

Coming back to **R2**: "Does anger have an adverse effect on lane change safety in level 3 automated vehicles upon a takeover request?", I will discuss lane departures, lane change durations and eye tracking data analysis.

In terms of the eye tracking analysis, I found that **H5:** "Glance frequency and duration on the vehicle mirrors will be less for angry drivers as compared to neutral drivers" was not supported as there were no significant differences between angry and neutral drivers. The eye tracking data did not show any significant indications of unsafe driving by angry drivers, but did conform with the fact that angry drivers drove faster.

In terms of lane departures, angry drivers had a numerically higher number of lane departures, but not significantly so. Higher lane departures could mean unsafe driving (Shen & Neyens, 2014). While at first glance supportive of **H4:** "Lane departures will be significantly more for angry drivers", it cannot be fully supported. Therefore, I cautiously state that **H4** was partially supported.

Lane change durations were expected to be lower for angry drivers. This was because anger is a high arousal emotion, but does not facilitate better driving behavior. This pointed towards rash, quick and unsafe takeovers by angry drivers. Interestingly, data suggests the opposite of **H3:** "Lane change duration will be significantly less for angry drivers". Even though H3 was not supported, further investigation into the safety of the lane change was indicate of unsafe driving behavior. Angry drivers may in fact have taken longer times because they stayed longer on the lane owing to the fact that steering wheel angles were lower for angry drivers. It is likely that this led to longer times on the driving lane and a closer drive to the obstacle.

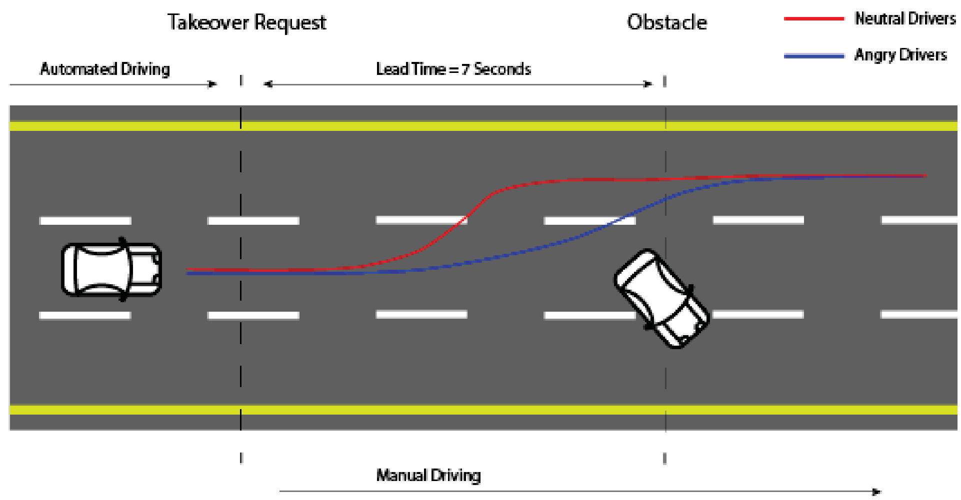


Figure 37: Diagram depicting Angry Driver vs Neutral Driver Behavior

Figure 37 depicts neutral driver behavior in comparison to angry drivers. Neutral drivers drove slower and had more time to react to the obstacle ahead. The slower neutral drivers also had larger steering wheel angles to change lanes which also showed better avoidance maneuvers.

Anger is also an emotion which would cause drivers to attribute mistake and negative experiences to factors outside themselves and is "other" directed as well as inciting aggressive behavior (Brave & Nass, 2003; Martin, Watson, & Wan, 2000; Roseman, 1996). Previous research has also shown that angry drivers are more certain about decisions and this can lead to errors due to unsafe decision making (Jeon, Walker, & Yim, 2014). Angry drivers are also less likely to be aware of critical information or potential hazards on or off road (Jeon et al., 2015).

Although previous studies have looked into takeover reaction time and quality in semi-automated vehicles (Gold et al., 2015; Kutchek & Jeon, 2019; Radlmayr et al., 2014), few have investigated the influence of affect on the takeover performance. The findings from this study fall in line with previous research on anger and its effects on driving performance (Du et al., 2019; Jeon, 2016; Jeon et al., 2011). The results from this study suggest that driving safety after the takeover of the vehicle can be negatively affected by anger.

5.5 MODELLING PREDICTIONS

The primary aim for modelling reaction times was to first add to previous literature on auditory warning modelling for takeover reaction times in semi-automated vehicles. Secondly, I wanted to compare differences between angry drivers' reaction times with the modelled reaction times. In terms of the modelled reaction time using the QN-MHP, I found that **H2:** "The modelled reaction time for takeover requests will be significantly different from the reaction time for angry drivers" was not supported.

First, as the empirical data showed, angry and neutral drivers' reaction times had no significant differences between them. **H2** stems from **H1:** "Reaction time for takeover requests will be longer for participants with induced anger". As a result, as **H1** was not supported, **H2** was not supported either. Therefore, angry drivers and neutral drivers were treated the same and were therefore analyzed together.

Secondly, the modelled reaction time was built on the idea that increasing fundamental frequency or number of repetitions of an auditory warning would result in increased perceived urgency and therefore reduced reaction times (Edworthy et al., 2000; Edworthy et al., 1991; Ko et al., 2019). The empirical data for reaction times of warnings with 8 repetitions per second did not show this pattern consistently, and therefore were removed from the correlation analysis. The resulting R-squared value of 0.68 indicated in nearly 70% similarities in the patterns of reaction times of empirical data with the modelled reaction times. This effort adds to previous research in modelling takeover reaction times in semi-automated vehicles to auditory warnings (Ko et al., 2019). This suggests further research into analyzing how auditory characteristics such as fundamental frequency, pitch range and number of repetitions affect modelled takeover reaction times in semi-automated vehicles would yield more accurate results. This would help design better takeover systems in the future.

5.6 LIMITATIONS AND FUTURE WORK

This study was conducted under a variety of constraints that limited the scope of its research in different ways.

First, although the driving simulator was of a moderately high fidelity, it is not the same as a real driving experience. This may have led to slightly different driving behaviors when compared to real life.

Next, when considering the emotion induction methodology, measuring physiological indicators of arousal or emotion would have increased the validity of this study, for example, S. M. Fakhrhosseini and Jeon (2019) measured heart rate (ECG) and oxygen level in frontal lobe using fNIRS to measure indicators of emotion. At the same time would also have been less ecologically valid since they were invasive. Methods such as facial emotion detection may help alleviate such issues. For future studies on the topic of takeover and affect it would be useful to be able to have measures to confirm perceived emotions from the emotion induction.

Coming to the auditory alert design, the large number of auditory alerts only allowed each auditory alert to be presented once to every participant. Additionally, due to each lap containing 3 different alerts, this study could not gauge perceived auditory characteristics of the sounds such as annoyance, intuitiveness, identifiability, urgency and helpfulness. This also prevented the comparison of applying workload metrics such as the NASA-TLX to compare the perceived workload of the auditory alerts. Future studies may consider comparing the perceived urgency in detail for affect induced drivers.

This study primarily compared takeovers in emergent scenarios for collision avoidance on a three-lane highway, which is a small but important subset of takeover actions that might be performed in semi-automated vehicles. It might be worth studying affect influence in performance for different driving and takeover scenarios. Additionally, traffic experienced was also kept constant during the study, which also might influence takeover performance especially when taking into consideration how safe a takeover is.

Future studies could also incorporate more emotions to understand different influences of affect on takeover performances in semi-automated vehicles. For example, Jeon, Walker, and Yim (2014) compared results of driving performance, and perceived workload in anger, fear and happiness affective states as well as a neutral state. Du et al. (2019) compared takeover performances for different affective states: namely, angry, sad, happy and calm and found that anger lead to the lowest readiness for takeover and aggressive driving while calm drivers drove smoothly and negotiated events appropriately.

Takeover is an important but short part of the collision avoidance that occurs in scenarios such as the one studied in this present thesis. Future research could look into modelling more motor actions performed by drivers to help predict performance and improve driver safety in future semi-automated vehicles.

Lastly, the Non-Driving Secondary (NDRT) was a visual and cognitive task that did not have a large overlap with the takeover warning perception task which was primarily an auditory task (Baddeley, 1992). It might be worth studying how different auditory stimuli or tasks such as music in the background, conversations with other passengers or phone calls and chats might influence the task performance.

5.7 CONCLUSION

Anger's influence on driver takeover performance in level 3 automated vehicles was measured using in a mid-fidelity simulator. From this study, it is evident that neutral driver slowed down more, which means they had more time to react and make safer lane change as shown in the higher steering wheel angles. Angry drivers drove faster, which could have high potential to lead to a collision hazard. This unsafe behavior is shown in the smaller steering wheel angles and the lack of time to react due to the higher speeds. A cautious implication of this study would be that angry drivers' behavior in takeover scenarios might be considered unsafe.

Automation in vehicles has increased in the past decade significantly, but until full automation is achieved, human interaction with automated will always be subject to the influence of affect. Measuring affect in vehicles will be important to identify and respond to affective states that negatively affect driving performance (M. Jeon & B. Walker, 2011;

Vasey, Ko, & Jeon). Studies into how the influence of affect can be mitigated such as M. FakhrHosseini, Landry, Tan, Bhattarai, and Jeon (2014) and (Jeon et al., 2015) would be helpful in designing safer automated vehicles.

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APPENDIX

A. APPEDIX A: DOCUMENTS

A1. IRB AUTHORIZATION (AMENDMENT PENDING FOR APPROVAL)

VIRGINIA TECH.

Division of Scholarly Integrity and Research Compliance
Institutional Review Board
North End Center, Suite 4120 (MC 0497)
300 Turner Street NW
Blacksburg, Virginia 24061
540/231-3732
irb@vt.edu
http://www.research.vt.edu/sirc/hrpp

MEMORANDUM

DATE: March 22, 2019

TO: Myounghoon Jeon

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires January 29, 2021)

PROTOCOL TITLE: Measuring the Usability of Multi-Modal Displays in Autonomous Vehicles

IRB NUMBER: **19-088**

Dear Investigator(s):

RE: Protocol Submission for WIRB Review

The Virginia Tech Institutional Review Board (IRB) office screened this study and determined that it is ready for WIRB review.

Please download the "Instructions for the PI to Transfer the VT IRB Protocol to WIRB":

https://secure.research.vt.edu/external/irb/wirb-submission-instructions.pdf

Please go to https://connexus.wcgclinical.com to complete the protocol submission process to the WIRB.

ATTENTION:

* Myounghoon Jeon MUST BE LISTED AS THE PI ON THE WIRB SUBMISSION.

* All references to the VT IRB (including phone number and email address) MUST be removed from all study documents and replaced with Western IRB - (800) 562-4789, help@wirb.com.

*Special instructions, if any, are included on the top of the next page.

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VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
An equal opportunity, affirmative action institution

SPECIAL INSTRUCTIONS:

*** This study has submitted a proposal for funding to the National Science Foundation. ***

Date*	OSP Number	Sponsor	Grant Comparison Conducted?
03/09/2019	PMHK6RGE	National Science Foundation (Title: NRI: INT: COLLAB: SCALA: Scalable Collaborative Affective interventionaL Autonomous System for Teenage Drivers)	Compared on 03/19/2019

* Date this proposal number was compared, assessed as not requiring comparison, or comparison information was revised.

If this protocol is to cover any other grant proposals, please contact the HRPP office (irb@vt.edu) immediately.

A2. SAMPLE EMOTION PARAGRAPHS

Adapted from (Jeon, Walker, & Gable, 2014).

ANGER

Example 1

I was so excited to start my first internship experience. I was assigned to develop a webpage for the company and I spent all nights to finish the assignment to meet the short deadline I was given. It was a startup company where everybody was busy and I had nobody to get a tip or feedback from for what I designed. After several attempts to ask for a feedback only to be brushed off, I decided to get it done and then ask for a final checkup instead. After finalizing the work, I reported my work to one of associates, and he showed an attitude of indifference towards my work and told me although not satisfied he'll report my work to the manager for me. I thanked him and continued on to other projects assigned for me. After two months, I was summoned to the manager that I didn't report any progress regarding my first assignment like all the other interns had. To my bewilderment, he told me that he had waited till now thinking that I needed more time to finish it and disappointed that I failed to do so. He even showed me an exemplary work done by another intern which looked exactly like mine! Then did I realize that the associate who I reported to was no associate but an intern who took credit.

Example 2:

This committee was a chance for me to finally show my ability to the senior directors. It was a chance I have been waiting for and had been preparing myself for it for a while now and it has been set for the next day. I had to stay up late to do the final touchups when without realizing, I suddenly fell asleep and it was already late for the meeting when I woke up. I nimbly packed all resources I organized last night and drove my car in a hurry. But after a while, a huge truck blocked the road and series of cars were waiting for that truck to make a U-turn. I saw there were not enough space for the truck and all cars had to back their car one by one to make more space during the already hectic morning hours. It was a disaster!

NEUTRAL

Example 1:

I went to the grocery store to pick up a new carton of milk to replace the one that ran out the day before and some ingredients to make my dinner. I entered the store and grabbed a grocery cart. First, I headed over to the pasta section and picked up a bag of pasta shells and a can of tomato sauce. Then, I went to the fresh produce area to pick out some vegetables for the pasta. Finally, I went down the dairy section to grab a carton of milk. I went to the cashier to check out, unloaded the groceries into the car and drove home.

Example 2:

I needed to pick up my sister from school. The route is one that I am very familiar with. I pulled out from my driveway and drove down my street. I made a right turn at the first stop sign and continued to drive until I reached the main entrance. Then, I turned left onto the main road. I drove down the main road outside my neighborhood and turned left at the third intersection. I continued to drive for about three miles and then made a right turn on the road where the school is located. I turned into the pick-up lane and waited for my sister to come outside. The traffic flow that day was relatively normal and I arrived on time as I had expected.

A3. INFORMED CONSENT FORM

IRB APPROVED
Mar 29, 2019

RESEARCH SUBJECT CONSENT FORM

Title:	Measuring the Usability of Multi-Modal Displays in Autonomous Vehicles
Protocol No.:	IRB # 19-088 WIRB® Protocol #20190849 19-088
Sponsor:	Virginia Polytechnic Institute and State University (Virginia Tech)
Investigator:	Myounghoon Jeon, PhD 519D Whittemore Hall (MC 0118) 1185 Perry Street Blacksburg, VA, 24061 United States
Daytime Phone Number:	906-231-5167 540-514-1994
24-hour Phone Number:	540-514-1994

RESEARCH CONSENT SUMMARY

You are being asked for your consent to take part in a research study. This document provides a concise summary of this research. It describes the key information that we believe most people need to decide whether to take part in this research. Later sections of this document will provide all relevant details.

What should I know about this research?

- Someone will explain this research to you.
- Taking part in this research is voluntary. Whether you take part is up to you.
- If you don't take part, it won't be held against you.
- You can take part now and later drop out, and it won't be held against you
- If you don't understand, ask questions.
- Ask all the questions you want before you decide.

How long will I be in this research?

We expect that your taking part in this research will last at most 1 hour and you (the participant) will be allowed to ask for breaks at any time during the experiment. If you are injured or fatigued from the experiment at any time, you may leave the experiment and no consequences will apply.

Why is this research being done?

The purpose of this research is to evaluate the effects of in-vehicle multimodal display interfaces on driving performance and the driver's state.

What happens to me if I agree to take part in this research?

Before you start the experiment:

In the study, you (the participant) will be brought to the driving simulator and will be allowed to adjust the seating for comfort. Thereafter, you will be briefed about the experiment & given a demographics questionnaire to fill. When you feel ready, the experimenter will prepare you for the experiment by attaching the necessary data collection devices which include the following: Eye tracker (Tobii Pro Glasses 2), heart rate monitor (Polar H7) and non-invasive brain imaging devices (NIRO 200NX, Hamamatsu Photonics).

Pre-screening:

When you are comfortable and ready to begin, the experimenter will start the simulator. You will be allowed to drive in the simulator to become familiar with its working. Before the actual study begins, you will have a short (2-3 minute) driving session as a simulation sickness test run. Before and after this run, you will fill out a simulation sickness questionnaire which will be used to check your eligibility to continue the study. Once successfully completed, the experimenter will begin the study.

The experimental procedure:

During the study, you will be allowed to drive in the simulator and will be required to react/respond to different multimodal displays such as sounds, visual displays or tactile displays (such as haptic feedback) in the vehicle in specific driving scenarios. Each scenario can include autonomous, semi-autonomous and non-autonomous driving scenarios that try to replicate real world driving situations. Each driving scenario would last approximately 5-20 minutes. After the completion of each scenario, you will be asked to fill out post-questionnaires about workload (NASA-TLX), and subjective experience of the study (user experience questionnaire).

Could being in this research hurt me?

This experiment is expected to present no more than minimal risk to you (the participant), however procedures may involve unforeseeable risks that are currently unforeseeable. During the study you may experience simulator sickness. Symptoms of simulator sickness include discomfort, drowsiness, disorientation, fatigue, and vomiting.

Before the actual driving scenario, you will have a short (2-3min) driving session as a simulation sickness test run. Before and after this run, you will fill out the simulation sickness questionnaire for screening purposes. Only those who passed the simulation sickness test will participate in the actual experiment. The experimenter will also give you enough time between scenarios to recover from simulator sickness effects if necessary and you can ask for breaks at any time during the experiment. If you feel that you are injured or fatigue from the experiment, you may leave the experiment and no consequences will apply.

Will being in this research benefit me?

It is not expected that you will personally benefit from this research.

What other choices do I have besides taking part in this research?

This research is not designed to diagnose, treat or prevent any disease. Your alternative is to not take part in the research.

DETAILED RESEARCH CONSENT

You are being invited to take part in a research study. A person who takes part in a research study is called a research subject, or research participant.

What should I know about this research?

- Someone will explain this research to you.
- This form sums up that explanation.
- Taking part in this research is voluntary. Whether you take part is up to you.
- You can choose not to take part. There will be no penalty or loss of benefits to which you are otherwise entitled.
- You can agree to take part and later change your mind. There will be no penalty or loss of benefits to which you are otherwise entitled.
- If you don't understand, ask questions.
- Ask all the questions you want before you decide.

Why is this research being done?

The purpose of this research is to evaluate the effects of in-vehicle multimodal display interfaces on driving performance and the driver's state.

About 100 subjects will take part in this research.

How long will I be in this research?

We expect that your taking part in this research will last at most 1 hour and you (the participant) will be allowed to ask for breaks at any time during the experiment. If you are injured or fatigued from the experiment at any time, you may leave the experiment and no consequences will apply.

What happens to me if I agree to take part in this research?

This study will take place at the Mind Music Machine Lab rooms at Whittmore Hall, 519A and 568.

Before you start the experiment:

In the study, you (the participant) will be brought to the driving simulator and will be allowed to adjust the seating for comfort. Thereafter, you will be briefed about the experiment. When you feel ready, the experimenter will prepare you for the experiment by attaching the necessary data collection devices which include the following: An eye tracker (Tobii Pro Glasses 2), heart rate monitor (Polar H7) and non-invasive brain imaging devices (NIRO 200NX, Hamamatsu Photonics).

Pre-screening:

When you are comfortable and ready to begin, the experimenter will start the simulator. You will be allowed to drive in the simulator to become familiar with its working. Before the actual study begins, you will have a short (2-3 minute) driving session as a simulation sickness test run. Before and after this run, you will fill out a simulation sickness questionnaire. Once successfully completed, the experimenter will begin the study.

The experimental procedure:

During the study, you will be allowed to drive in the simulator and will be required to react/respond to different multimodal displays such as sounds, visual displays or tactile displays (such as haptic feedback) in the vehicle in specific driving scenarios. Each scenario can include autonomous, semi-autonomous and non-autonomous driving scenarios that try to replicate real world driving situations. Each driving scenario would last approximately 5-20 minutes. After the completion of each scenario, you will be asked to fill out post-questionnaires about workload, situation awareness, and usability.

What are my responsibilities if I take part in this research?

If you take part in this research, you will be responsible to participate in the experiment at most an hour and you could ask breaks at any time during the experiment. If you are injured or fatigue from the experiment, you could leave the experiment and no consequence will apply.

Could being in this research hurt me?

This experiment is expected to present no more than minimal risk to you (the participant). During the study you may experience simulator sickness. Symptoms of simulator sickness include discomfort, drowsiness, disorientation, fatigue, and vomiting.

Before the actual driving scenario, you will have a short (2-3min) driving session as a simulation sickness test run. Before and after this run, you will fill out the simulation sickness questionnaire for screening purposes. Only those who passed the simulation sickness test will participate in the actual experiment. The experimenter will also give you enough time between scenarios to recover from simulator sickness effects if necessary and you can ask for breaks at any time during the experiment. If you feel that you are injured or fatigue from the experiment, you may leave the experiment and no consequences will apply.

Will it cost me money to take part in this research?

No.

Will being in this research benefit me?

There are no benefits to you from your taking part in this research. We cannot promise any benefits to others from your taking part in this research. However, participation in this study will contribute to our understanding of how to best design multi modal interfaces in vehicles.

What other choices do I have besides taking part in this research?

This research is not designed to diagnose, treat or prevent any disease. Your alternative is to not take part in the research.

What happens to the information collected for this research?

We may publish the results of this research. However, we will keep your name and other identifying information confidential. We protect your information from disclosure to others to the extent required by law. We cannot promise complete secrecy. Your private information will be shared with individuals and organizations that conduct or watch over this research, including:

- The research sponsor
- People who work with the research sponsor
- Government agencies, such as the Food and Drug Administration
- The Institutional Review Board (IRB) that reviewed this research

Data or specimens collected in this research might be reidentified and used for future research or distributed to another investigator for future research without your consent.

There are no plans to disclose clinically relevant research results, including individual research results, to you.

Who can answer my questions about this research?

If you have questions, concerns, or complaints, or think this research has hurt you or made you sick, talk to the research team at the phone number listed above on the first page.

This research is being overseen by an Institutional Review Board ("IRB"). An IRB is a group of people who perform independent review of research studies. You may talk to them at (800) 562-4789, help@wirb.com if:

- You have questions, concerns, or complaints that are not being answered by the research team.
- You are not getting answers from the research team.
- You cannot reach the research team.
- You want to talk to someone else about the research.
- You have questions about your rights as a research subject.

What if I am injured because of taking part in this research?

This experiment is expected to present no more than minimal risk to you (the participant). During the study you may experience simulator sickness. Symptoms of simulator sickness include discomfort, drowsiness, disorientation, fatigue, and vomiting.

If you feel that you are injured or fatigue from the experiment, you may leave the experiment and you should seek medical treatment from your normal health care provider or call 911 for emergencies. No research related consequences or loss of benefits to which you are otherwise entitled will apply, however, you will be billed for any medical costs not reimbursed by your insurance provider.

Can I be removed from this research without my approval?

The person in charge of this research can remove you from this research without your approval. Possible reasons for removal include:

- It is in your best interest
- You have a side effect that requires stopping the research
- You are unable to keep your scheduled appointments

We will tell you about any new information that may affect your health, welfare, or choice to stay in this research.

What happens if I agree to be in this research, but I change my mind later?

If you decide to leave this research, contact the research team so that the investigator can stop continuing the experiment. It is important for you to know that you are free to withdraw from this study at any time without penalty.

Will I be paid for taking part in this research?

For taking part in this research, you may be paid up to a total of 10$. If you could not finish the experiment, you will be compensated for the time you participated.

Statement of Consent:

Your signature documents your consent to take part in this research.

Signature of adult subject capable of consent	Date
Signature of person obtaining consent	Date

A4. STUDY ADVERTISEMENT FLYER

VIRGINIA TECH.

20190849
#24142861.0

IRB Approved at the Protocol Level
Mar 29, 2019

Autonomous Vehicle Driving Simulator Study

Participants Needed

Volunteers needed for the Mind Music Machine Lab's study in determining the usability and effect of In-Vehicle displays (Visual, Auditory & Tactile) on Driver state and performance. During the study, you will be asked to drive in a driving simulator environment. You may be asked to wear eye trackers, heart rate monitors and non-invasive brain activity imaging devices. Your driving performance may be recorded with cameras/screen recordings during the study.

Eligibility

- Active driver with a valid U.S License
- More than 2 years of driving experience
- Age 18+, Good Health
- Normal Vision and Hearing

Duration

The study should take about 1 hour, and you will receive $10 compensation. Participation in this study is voluntary and confidential. If you are interested in participating, please contact **Harsh Sanghavi (harshks@vt.edu).**

Warning

There is a risk of induced motion sickness when using a driving simulator. If you are susceptible to **severe motion sickness, migraines, epilepsy, dizziness or blurred vision, or are pregnant**, then you should not volunteer.

Mind Music Machine

Research Protocol approved by Western IRB (WIRB)

(800) 562-4789, help@wirb.com

B. APPENDIX B: SURVEYS

B1. DEMOGRAPHICS SURVEY

Age

Gender

- Male
- Female
- other

How many years have you held a full U.S. driver's license?

Do you have any vision problems?

- Yes
- Corrected (lenses/glasses)
- No

Do you have any hearing problems?

- Yes
- Corrected (hearing aid)
- No

How often do you drive?

- every day
- few times a week
- few times a month
- few times a year

B2. EMOTIONAL LIKERT SCALE SURVEY

Emotion Likert Scale

Circle the response that best characterizes how you strongly you feel the emotions given below.
Where: 1 = Not at all, 5 = Neutral, 7 = Strongly Feel

	Not at All			Neutral			Strongly Feel
Fear	1	2	3	4	5	6	7
Happy	1	2	3	4	5	6	7
Angry	1	2	3	4	5	6	7
Depressed	1	2	3	4	5	6	7
Confused	1	2	3	4	5	6	7
Embarrassed	1	2	3	4	5	6	7
Urgent	1	2	3	4	5	6	7
Bored	1	2	3	4	5	6	7
Relieved	1	2	3	4	5	6	7

B3. SIM SICKNESS QUESTIONNAIRE

20190849
#24142864.0

IRB Approved at the
Protocol Level
Mar 29, 2019

<PRE-QUESTIONNAIRE>

Personal Comfort Checklist

Please read the following list of symptoms carefully and consider the scales provided.
Please mark the number on the scale which best describes how you would rate your current feelings of each symptom.
0 = no symptom 10 - unbearable level of symptom

I feel…	Response
1. sick to my stomach	
2. faint-like	
3. annoyed/ irritated	
4. sweaty	
5. queasy	
6. lightheaded	
7. drowsy	
8. clammy/ cold sweat	
9. disoriented	
10. tired/fatigued	
11. nauseated	
12. hot/warm	
13. dizzy	
14. like I am spinning	
15. as if I might vomit	
16. uneasy	
17. floating	

Contatct: Western IRB (WIRB, contact information [(800) 562-4789, help@wirb.com]