MULTISENSORY PROCESSING IN SIMULATED DRIVING

MULTISENSORY PROCESSING IN SIMULATED DRIVING

By MARYAM PANDI, B.Sc.

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Descriptive Note

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Lay Abstract

Multisensory processing (combining information from different sensory systems) is not well understood in realistic tasks such as driving. A simulated environment consisted of a straight, two-lane road was used for this study. The task was to drive in the center of the right lane and maintain a constant speed, slowing down for occasional speed bumps. We examined differences in driving performance under four sets of sensory cues: visual only, visual and auditory, visual and physical motion, and visual, auditory and physical motion. The visual information was manipulated across two experiments: first, participants drove in daylight in sunny weather, providing excellent visual information. Next, visual information was compromised by providing dark and stormy weather conditions. In both experiments we observed an advantage of multisensory information, an effect that was enhanced when visual information was compromised. Auditory cues were especially effective in improving driver control.

Abstract

Studies that explore integration of visual, auditory or vestibular cues, are derived from stimulus detection and discrimination tasks in which stimuli are selective and controlled. Multisensory processing is not as well understood in more dynamic and realistic tasks such as driving. As visual information is the dominant source of information when controlling a vehicle, we were interested in the contribution of auditory and physical motion (vestibular and proprioceptive) information to vehicle control. The simulated environment consisted of a straight, two-lane road and the task was to drive in the center of the right lane and maintain a constant speed, slowing down for occasional speed bumps. We examined differences in driving performance under four sets of sensory cues: visual only, visual and auditory, visual and physical motion, and visual, auditory and physical motion. The quality of visual information was manipulated across two experiments. In Experiment 1, participants drove in daylight in sunny weather, providing excellent visual information. In Experiment 2, visual information was compromised by providing dark and stormy weather conditions. In both experiments we observed an advantage of multisensory information, an effect that was enhanced when visual information was compromised. Auditory cues were especially effective in improving driver control.

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Deceleration of Academic Achievement

My supervisor, Judith Shedden, Martin von Mohrenschildt, and myself designed the research conducted in this thesis; therefore, the pronoun “we” was used throughout the dissertation. With the guidance of Dr. Shedden I conducted literature review, proposed research questions, and hypotheses. I performed recruiting, qualitative and quantitative data gathering with the help of undergraduate students at Dr. Shedden’s lab, Hannah Song, and Anisha Khosla. I performed all analyses. I wrote this thesis under supervision of Dr. Shedden.

1 Introduction

Driving is a complex task in which stimuli from different modalities contribute to self-motion perception. In forming this perception, information from multiple sensory systems is integrated (Bremmer, 2011; Britten, 2008). It has been shown that visual information can provide reliable information on both direction and magnitude of self-motion (Butler, Smith, Campos, & Bülthoff, 2010; Campos, Butler, & Bülthoff, 2012; Fetsch, Turner, DeAngelis, & Angelaki, 2009; Frenz & Lappe, 2005; Warren & Hannon, 1988), and visual information about self-motion is often dominant over other information (Berthoz, Pavard, & Young, 1975; Fetsch et al., 2009). However, vestibular cues also provide information about change in magnitude or direction of speed (Angelaki, 2004; Angelaki & Cullen, 2008; Berthoz et al., 1975; DeAngelis & Angelaki, 2012), and therefore enhance the perception of self-motion (Benson, Spencer, & Stott, 1986; Guedry, 1974, 1977; Telford, Howard, & Ohmi, 1995). Likewise, auditory cues can enhance self-motion perception by helping to differentiate between visual cues of self-motion and other object-motion (Calabro, Soto-Faraco, & Vaina, 2011; Väljamäe, Larsson, Västfjäll, & Kleiner, 2008). Particularly during driving tasks, auditory cues of wind, engine, and movement of tires on the road contain rich information about magnitude of speed and acceleration of the car (Merat & Jamson, 2011; Ramkhalawansingh, Keshavarz, Haycock, Shahab, & Campos, 2016). Previous studies show that speed management is a key factor in road safety, and has a well-established relationship with risk of crash (Aarts & Van Schagen, 2006) and fatality rate (Joksch, 1993).

However, sensory cues are not always reliable. For instance, visual cues provide less information about self-motion in low contrast conditions, such as in darkness (Warren Jr, Kay, Zosh, Duchon, & Sahuc, 2001) or fog (Snowden, Stimpson, & Ruddle, 1998). Moreover, visual cues provide information about distance while the brain estimates the speed based on perception of distance and time (Recarte & Nunes, 1996). Therefore, in driving context and in absence of secondary feedback such as speedometer or auditory cues, individuals' perception of speed is less accurate (Horswill & Plooy, 2008). Drivers and passengers tend to underestimate speed (Conchillo, Recarte, Nunes, & Ruiz, 2006; Evans, 1970; Milošević, 1986; Triggs & Berenyi, 1982) , and this effect can be stronger in diving simulators (Godley, Triggs, & Fildes, 2002). Even when movement does not produce a direct auditory cue, indirect information obtained using the auditory system, such as wind and engine noise, improves vection experience, particularly during driving (Horswill & Plooy, 2008; Matthews & Cousins, 1980; Merat & Jamson, 2011). The vestibular sensory system alone does not provide reliable information about motion vection when speed is constant (i.e., without acceleration or de-acceleration) (Berthoz et al., 1975; Siegle, Campos, Mohler, Loomis, & Bülthoff, 2009). Moreover, it is difficult for the human vestibular system to distinguish between the translation and the tilt perpendicular to the direction of gravity, particularly in low frequency motions (DeAngelis & Angelaki, 2012). Therefore, in absence of visual cues, linear acceleration can be confused with tilt or pitch (Previc, Varner, & Gillingham, 1992; Wolfe & Cramer, 1970). This indicates that vestibular cues alone are not sufficient to form an accurate perception of self-motion in certain driving situations.

The process of multisensory integration of information from different sensory modalities provides a more reliable and precise perception of self-motion compared to a situation in which information is available from only a single sensory input (Butler et al., 2010; Cullen, 2012; Fetsch et al., 2009; Morgan, DeAngelis, & Angelaki, 2008). Multisensory perception is robust, even in scenarios where one or more sensory input is providing unreliable information (DeAngelis & Angelaki, 2012; Dichgans & Brandt, 1978; Rowland & Stein, 2014; Siegle et al., 2009).

Several previous studies have attempted to investigate different aspects of multisensory integration in the context of driving. Some studies concluded that lack of auditory cues contribute to speed underestimation (Denjean, Roussarie, Kronland-Martinet, Ystad, & Velay, 2012; Evans, 1970; Matthews & Cousins, 1980), while others did not find a significant difference in the absence of auditory stimuli (Horswill & McKenna, 1999; McLane & Wierwille, 1975).

More recently, researchers have investigated the impact of auditory or vestibular cues on driving performance in the context of different road conditions among younger and older adults. They found that addition of auditory cues reduced standard deviation of speed among both age groups and road conditions (Ramkhalawansingh et al., 2016). However, while adding vestibular cues to a driving simulator can improve speed maintenance in older adults, it weakened lane-keeping performance (Ramkhalawansingh, Keshavarz, Haycock, Shahab, & Campos, 2017). Moreover, when the authors compared trimodal (visual, auditory, and vestibular) with bimodal (visual and auditory or visual and vestibular) cue conditions, no significant improvement in measures of driving performance were identified (Ramkhalawansingh, 2018). These are interesting findings which highlight the necessity for further investigation into the role of multisensory integration in driving.

In this study, we explored the effect of visual, auditory, and physical motion (vestibular and proprioceptive) cues on driving performance in two experiments. Our methods did not distinguish between vestibular and proprioceptive information and in the remainder of the paper we refer to the physical motion stimulus as vestibular. Two main questions were addressed regarding the control of the vehicle in terms of speed, acceleration and lateral position across the timeline of the driving task, including control of the vehicle as participants decelerated and accelerated around speed bumps. First, considering the visual only condition as a baseline, we observed the effect on driving performance when vestibular and/or auditory cues were also provided. Second, we examined driving performance across the same measures when the normally dominant visual cues were compromised. Specifically, we compared driving performance in clear and sunny weather conditions (Experiment 1) with driving performance in dark and stormy weather conditions (Experiment 2).

We used a driving simulator to manipulate the sensory cues in a highly controlled environment, with minimum risk, while making sure the scenarios presented were as realistic as possible. Participants were observed while driving on a straight highway (no turns) defined by receding parallel lines that converged in a distant vanishing point. There were yellow dashed lines demarking the left and right lanes and fence posts on both sides of the highway to provide visual cues to speed. We compared driving performance under four different conditions: visual cues only, visual and auditory cues (e.g., engine sound), visual and vestibular cues (e.g., road surface noise and vehicle movement which provided both vestibular and proprioceptive information), and visual, auditory, and vestibular cues. Based on previous research, we hypothesized that vestibular and auditory cues should improve driving performance when compared to the visual-only condition (Experiment 1), and that these effects should be enhanced when visual information is compromised in stormy weather conditions (Experiment 2). We were especially interested in how this improvement might be manifested across the measures of speed, acceleration, lateral position, and vehicle control around the speed bump hazards.

2 Experiment One

2.1 Materials and Methods

2.1.1 Participants

Eighty participants were recruited from the McMaster University psychology participant pool and the McMaster community. Those recruited from the participant pool were compensated with course credits. All participants had a valid driving license (e.g., at least G2 level in Ontario, Canada), had normal or corrected-to-normal vision, and were screened based on self-report for history of major problems with vertigo, motion sickness or claustrophobia. Twelve participants were excluded from the analysis (5 outliers and 7 based on reported symptoms of discomfort with the simulated environment). The proportion (.09) of participants who reported discomfort with the simulated motion is comparable to other driving simulator studies (Cassavaugh, Domeyer, & Backs, 2011; Reed-Jones, Vallis, Reed-Jones, & Trick, 2008; Stoner, Fisher, & Mollenhauer, 2011). The 68 participants included in the analyses were 35 (51.5%) females and 19 ± 2.5 years of age (range = 17 – 32). Fifty-four (79.4%) participants identified as right-handed and 14 (20.6%) as left-handed. This experiment was approved by the Hamilton Health Research Ethics Board and complied with the Canadian tri-council policy on ethics.

2.1.2 Apparatus and Stimuli

Visual System: Visual stimuli were presented on three 42” (diagonal) LCD screens with a resolution of 1920 x 1080 pixels and a refresh rate of 60 Hz, positioned approximately 130 cm from the seated participant, with a field-of-view of 35° vertically and 120° horizontally. The visual simulation was coded in C++ using Vega Prime. The visual display presented a daylight view of a two-lane rural road (straight with no curves); there were guardrails and grassy areas on both sides of the road (Figure 2). Occasional light grey speed bumps extended across both lanes; the profile of the speed bumps was an arc 40 cm wide and 15 cm high. The effect of driving over a speed bump was reflected as both visual and physical motion. During training, a digital speedometer was displayed in the lower 20% of the center of the middle screen.

Figure 1. Motion platform and simulator system used for this study

Figure 2. Visual stimuli presented to participants inside the simulator

Auditory System: Auditory stimuli were presented through 4 Bose speakers (Bose Corp., Framingham, MA, USA). Two speakers were in front of the participant, placed at an altitude of 28° with azimuths of ±20°, at a distance of 150 cm from the participant's head. The other two speakers were behind the participant, placed at an altitude of 12° with azimuths of ±160°, at a distance of 130 cm from participant's head. The auditory stimulus was a looped recording of the engine sound of a standard 4-cylinder car. The pitch of the sound was scaled linearly based on RPM of the engine. For example, at 80 km/h the sound pressure level was 70 decibels.

Motion System: To generate vestibular motion cues, the simulator pod rested on a 6 degrees-of-freedom Stewart platform (6DOF2000E, MOOG Inc., Elma, NY), capable of moving 1000 kg with 0.6 g (Figure 1). A combination of pitch angle and longitudinal acceleration was used to simulate braking and accelerating to produce the perception of acceleration experienced in a real car; this was achieved via classic motion cuing filter implementation with a network of tuned filters. The vehicle dynamics were derived based on a rigid body mechanics model and simulated in C++ using a solid body simulation package (ODE). To convey vibrations due to the texture of the road, physical motion noise with amplitude proportional to speed was added to 3 directions of linear acceleration (surge, heave, and sway).

Data acquisition: There were 2 cameras inside the pod; one provided a front view of the participant and the other one provided a bird's eye view of the interior. An intercom system allowed communication between the participant and the experimenter throughout the experiment. The motion simulator was equipped with a basic driving interface consisting of a bucket car seat with Logitech steering wheel and gas and brake pedals (Logitech International S.A., Lausanne, Switzerland). Speed, lateral position (measured as distance from center), gas pedal position, and brake pedal position, were recorded at 60 Hz.

2.1.3 Procedure

After obtaining written consent and demographic information, participants were seated in the motion pod and familiarized with the driving process. Each session was approximately 30 minutes in duration; this consisted of five 4-minute trials plus variable rest periods between each block. We made sure that every participant received adequate rest between blocks to minimize any symptoms of discomfort due to simulator motion. Following the completion of the session, a shortened version of the Simulator Sickness Questionnaire (Kennedy, Lane, Berbaum, & Lilienthal, 1993) was used to record symptoms of simulator sickness.

The first block of each session was a training block which presented Visual, Auditory, and Motion (VAM) information. Note that Motion (M) is used to indicate the physical motion of the simulator pod that produced vestibular and proprioceptive cues. The remaining 4 experimental blocks presented 4 different sensory conditions: Visual only (V), Visual and Auditory (VA), Visual and Motion (VM), and Visual, Auditory and Motion (VAM). The order in which the experimental blocks were presented was counterbalanced across participants, with the constraint that the VAM experimental block would not be presented immediately subsequent to the VAM training block. In all blocks, participants were instructed to drive at a specified target speed and to stay in the center of the right lane. A series of 4 speed bumps were presented approximately every 3600 frames, which worked out to approximately one per minute depending on speed. Participants were instructed to reduce speed when approaching the speed bumps (as they would do in real driving) and return to the target speed after each speed bump. The task instructions were to decelerate for the speed bumps, to pass over the speed bumps as smoothly as possible, and then to resume target speed. A heads-up sign was provided 50 meters before each speed bump that read “Slow down, speed bump ahead”.

The training block presented the Visual, Auditory and Motion (VAM) condition to familiarize participants with the simulator environment, including the associated visual, auditory, and vestibular perceptions associated with different speeds. Participants were instructed to maintain a constant target speed of 60, 80, or 100 km/h; this target speed was provided orally through the intercom immediately after each of the 4 speed bumps in the training block, in the following order: 60, 80, 100, and 80. The digital speedometer was presented in the training block only; no speedometer was presented in the experimental blocks.

In each of the 4 experimental blocks, participants were instructed to reach and maintain a speed of 80 km/h in the absence of the speedometer. Instructions regarding staying in the center of the right lane and slowing down for speed bumps were the same as described for the training block. A brief scheme of the study design is shown in Figure 3, illustrating one possible order of sensory conditions.

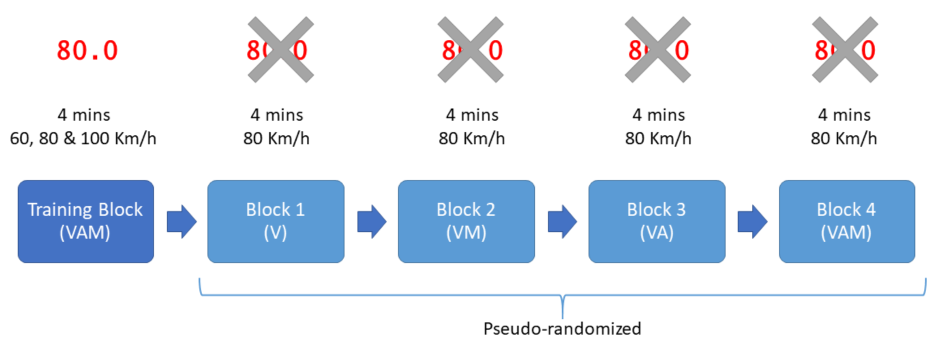


Figure 3. Overview of study's procedure. The digital speedometer was present in the training block only.

2.1.4 Analysis and Segmentation of data

Vehicle speed was recorded at 60 Hz. To aid in visualizing the speed data over the course of the 4-minute trial, Figure 4 illustrates average speed profiles for each sensory condition. The speed profiles were used as a basis for data segmentation.

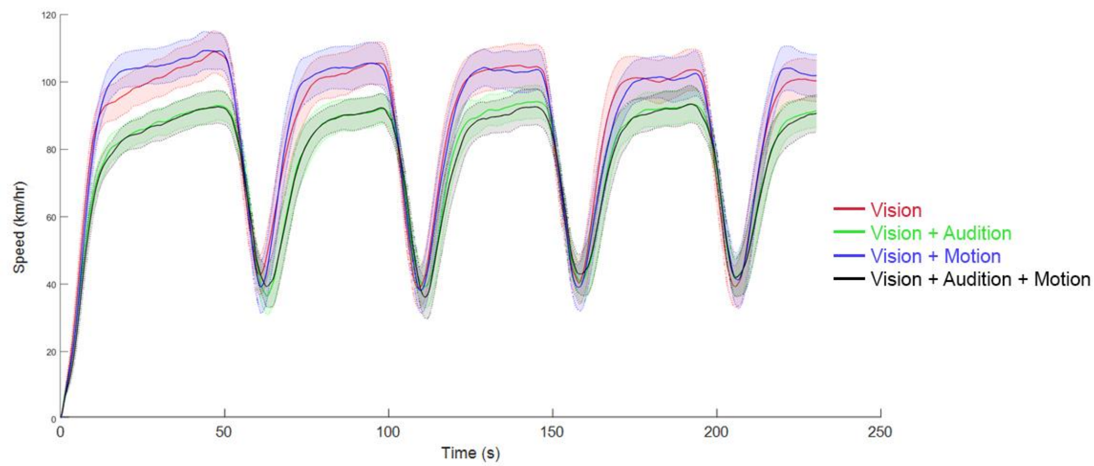


Figure 4. Speed profile and 95% confidence intervals for Experiment 1 (sunny weather).

Data were segmented into two sections: (1) between the speed bumps, over which the task was to maintain the target speed, and (2) across the speed bumps. This was achieved based on deceleration before the speed bump and acceleration to target speed after the speed bump. The beginning of each segment was marked as the first point after crossing the speed bump x at which the acceleration reached zero ($\pm 0.1 \frac{m}{s^2}$) and speed was at least half of maximum value (ie., end of accelerating marked with a green "x" in Figure 5). The end of each segment was marked as the last point before reaching the speed bump $x +$

1, at which acceleration reached zero ($\pm 0.1\frac{m}{s^2}$) and speed was at least half of maximum value (ie., start of decelerating marked with a red “x” in Figure 5).

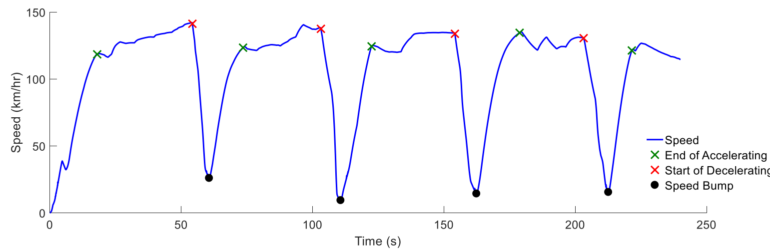


Figure 5. Result of applying segmentation criteria on a single set of speed data.

We used finite difference approximation to calculate acceleration. Numerical differentiations are algorithms for estimating the derivative of a mathematical function using the values of the function rather than its definition. The simplest method for numerical differentiation is finite difference approximation. We used a two-point formula to compute the slope of the secant line across a 10 data point moving window $(t-5, speed(t-5))$ and $(t+5, speed(t+5))$ to calculate acceleration:

$$acceleration = \frac{speed(x+5) - speed(x-5)}{10}$$

The estimate of error is proportional to $(\frac{5}{60})^2$, given 60 Hz resolution; the slope of the secant line approaches the slope of the tangent line as this error becomes smaller. The average acceleration profiles for all participants are shown in Figure 6. The positive values of acceleration denote an increase in speed, while the negative values indicate a reduction.

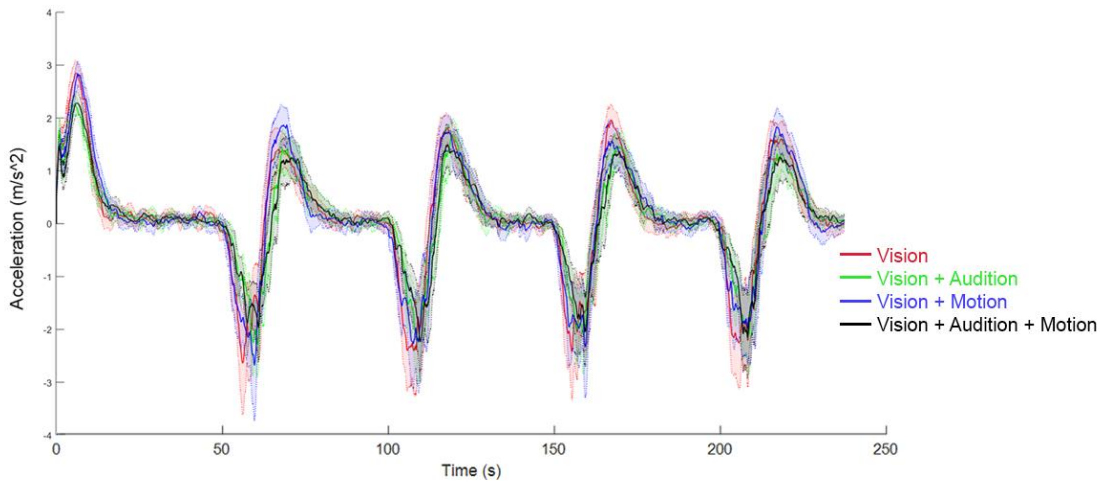


Figure 6. Acceleration profile; shading indicates 95% confidence intervals.

2.2 Results

A repeated measures design with sensory condition as the independent variable included four levels: Visual only (V), Visual and Auditory (VA), Visual and Motion (VM), or Visual, Auditory and Motion (VAM). Repeated-measures ANOVA's were used to compare the four sensory conditions on each measure of driving performance. Dependent variables measured driving performance between the speed bumps (e.g., mean speed, speed variability, acceleration, lateral position, and lateral position variability) and driving performance at the speed bumps (e.g., speed of crossing the speed bumps). A further set of analyses, presented in the Appendix, quantified the speed profile based on the transient response characteristics around the speed bumps.

A Bonferroni correction factor was applied to all post hoc tests, to adjust the initial $\alpha = 0.05$ threshold. The Greenhouse–Geisser adjustment for violations of sphericity (as determined by Mauchly's test of sphericity) was applied in all cases where sphericity was violated, in which case epsilon (ε) is reported and the results are presented with original degrees of freedom and adjusted p values. Bar graphs for both Experiments 1 and 2 are presented together in Figure 8.

2.2.1 Mean Speed

Average of speed for each sensory condition was calculated for the section between speed bumps, over which the task was to maintain the target speed. Speed differed across the sensory conditions, $F(3, 201) = 33.241, p < .0005, \eta_p^2 = .335, \varepsilon = .849$, such that mean driving speed was significantly faster during V and VM conditions, ($M = 103.1, \mathrm{SE} = 2.58$ and $M = 102.4, \mathrm{SE} = 2.49$, respectively) compared to VA and VAM ($M = 91, \mathrm{SE} = 2.09$ and $M = 90.7, \mathrm{SE} = 2.30$, respectively). There was no significant difference between V and VM or between VA and VAM. Although speed in all four sensory conditions was greater than the target speed of 80, providing auditory information appeared to improve speed control. The vestibular cue did not influence mean speed.

2.2.2 Speed Variability

Speed variability was calculated based on the weighted average of the standard deviation of speed between speed bumps. The pattern for speed variability is similar to mean speed. There was a difference across sensory conditions,

$F(3,201) = 15.9, p < .0005, \eta_p^2 = .194, \varepsilon = .811$, which can be explained by greater variability during V and VM conditions, ($M = 6.23, SE = 0.33$ and $M = 6.5, \mathrm{SE} = 0.32$ respectively) compared to VA and VAM ($M = 4.82, \mathrm{SE} = 0.25$ and $M = 4.69, \mathrm{SE} = 0.23$ respectively). There was no significant difference between V and VM or between VA and VAM. Thus, auditory information, but not vestibular information, improved both mean speed and variability of speed across these segments.

2.2.3 Acceleration

Average of absolute value of acceleration between speed bumps was calculated as another measure for driving performance. While speed variability is a good measure to quantify the size of speed deviations from mean speed over a period of time, acceleration provides the pace of these deviations over time, further distinguishing between sudden and gradual changes. We examined the average of the absolute value of acceleration to integrate into a single measure the acceleration (positive acceleration) and deceleration (negative acceleration) produced by operation of the gas and brake pedals. There was a difference across sensory conditions, $F(3,201) = 14.73, p < .0005, \eta_p^2 = .182, \varepsilon = .857$, that can be attributed to presence of higher acceleration in V and VM conditions, ($M = 0.445, \mathrm{SE} = 0.024$ and $M = 0.491, \mathrm{SE} = 0.026$, respectively) compared to VA and VAM ($M = 0.379, \mathrm{SE} = 0.020$ and $M = 0.382, \mathrm{SE} = 0.020$, respectively). There was no significant difference between V and VM or between

VA and VAM. These results are consistent with previous measures, showing that vestibular cues do not improve driving performance in terms of speed, speed variability and acceleration, while auditory cues do so.

2.2.4 Speed of Crossing the Bumps

Median speed of crossing the bumps in each trial was used to further understand how participants modify their speed in presence of different sensory cues. The statistically significant effect of sensory condition on this measure, $F(3{,}201) = 171.8, p = .002, \eta_p^2 = .07$, was the result of higher speed when crossing the bumps in V condition, ($M = 23.54, \mathrm{SE} = 1.82$) compared to VAM ($M = 19.74, \mathrm{SE} = 1.69$). On the other hand, there was no significant difference between other pairs of sensory conditions, VA ($M = 22.62, \mathrm{SE} = 1.72$) and VM ($M = 21.74, SE = 1.83$), indicating that adding motion or auditory cues alone did not decrease the speed of crossing the bumps. However, together the information from vision, audition, and physical motion was effective in reducing speed across the hazards compared to vision alone.

2.2.5 Lateral Position

Average of lateral position in each trial was used to determine the position of participants’ vehicle on the virtual road. The results show that the sensory condition did not have a significant effect on this measure, $F(3{,}201) = 1.304, p = .274, \eta_p^2 = .019$, and average position on the road was not dependent on sensory cues present V ($M = 1.92, \mathrm{SE} = 0.03$), VA ($M = 1.93, \mathrm{SE} = 0.03$), VM ($M = 1.93, \mathrm{SE} = 0.03$) and VAM ($M = 1.96, \mathrm{SE} = 0.03$).

2.2.6 Lateral Position Variability

The final driving performance measure was standard deviation of lateral position, which is a measure of lane keeping control. Lateral position variability was dependent on sensory condition, $F(3,201) = 8.091, p < .0005, \eta_p^2 = .108$. In particular, variability was higher in V condition, ($M = 0.332, \mathrm{SE} = 0.010$) compared to VM and VAM ($M = 0.30, \mathrm{SE} = 0.010$ *and* $M = 0.30, \mathrm{SE} = 0.010$, respectively). Variability was also higher in VA ($M = 0.298, \mathrm{SE} = 0.010$) in comparison to the VAM condition ($M = 0.321, \mathrm{SE} = 0.012$) . There was no significant difference between lateral position variability among other pairs of sensory conditions. Thus, it appears that physical motion cues help to reduce the variability in lane position.

2.3 Discussion

Results from mean speed, speed variability, and mean magnitude of acceleration revealed that auditory cues improved individuals' estimation of self-motion speed, as well as measures of speed control (speed variability and mean acceleration magnitude). However, the addition of vestibular cues alone did not have an effect on speed, nor on speed control.

Speed of crossing the bumps was reduced significantly with addition of each sensory cue, with the smallest values corresponding to the VAM (Visual, Auditory, and Motion) condition.

As was expected, vestibular and auditory cues did not have an effect on mean lateral position, since participants mainly rely on vision to stay, on average, in the middle of the lane. However, variance around the middle of the lane (lateral position variability) was affected by the presence of vestibular information. Lateral position variability decreased with addition of vestibular cues, suggesting that participants do use vestibular information to guide lateral position on the road. Auditory cues in the sunny weather did not have an effect on lateral position variability; this is a less interesting observation because the auditory cue did not carry any information about lateral position (however, see Experiment 2).

The results of the first study indicated that the addition of auditory cues provided information that changed driving performance on several measures. Vestibular cues affected some measures (speed and variability of lateral position). We know that perception of self-motion is often dominated by visual information, therefore it is of interest how the measures in Experiment 1 might change given compromised visual conditions as one might experience during stormy weather. Experiment 2 examined the effect of compromised vision in presence of auditory and/or vestibular cues. To achieve this, we replicated the conditions in Experiment 1 except that visually the participants drove in stormy weather with blurred side windows and heavy rain.

3 Experiment Two

3.1 Materials and Methods

3.1.1 Participants

Eighty participants were recruited from the same pool as previously mentioned, with same inclusion criteria. Fifteen participants were excluded from the analysis (4 outliers and 11 based on reported symptoms of discomfort with the simulated environment). The 65 participants included in the analyses were 20.5 ± 3.5 years of age (range = 18 – 39), and were 35 (53.8%) females. Sixty-three (97%) participants identified as right-handed and 2 (3%) as left-handed

3.1.2 Apparatus and Stimuli

The apparatus and stimuli were the same as described in Experiment 1, with only one change. Visual cues were modified in this study to produce a dynamic simulation that approximated driving in poor weather. This effect was achieved by adding a texture of a rainy window as a semitransparent mask on top of the renders in each display, as can be seen in Figure 7. This mask blocked 95% of visibility of both side windows, while covering the windshield outside of the range of wipers. A realistic dark sky, actively falling rain, and fog on the horizon were simulated using VEGA Prime, producing an effect similar to driving with no headlights in stormy weather conditions.

Figure 7. Visual stimuli presented to participants inside the simulator in the second experiment

3.1.3 Design, Procedure, Segmentation of data, and Analyses

Design, procedure, segmentation of data, and analyses were the same as described for Experiment 1. The only difference in Experiment 2 was the visual display, as described in section 3.1.2.

3.2 Results

Repeated measures ANOVAs were used to compare different measures of driving performance between sensory conditions (V, VA, VM, and VAM). The Bonferroni correction factor was applied to all post hoc tests, to adjust the initial $\alpha = 0.05$ threshold. The Greenhouse–Geisser adjustment for violations of sphericity (as determined by Mauchly's test of sphericity) was applied in all cases where sphericity was violated, in which case epsilon (ε) is reported and the results were presented with original degrees of freedom and adjusted p values.

3.2.1 Mean Speed

The average of speed varied among sensory conditions, $F(3, 192) = 47.95, p < .0005, \eta_p^2 = .435, \varepsilon = .866$, with participants driving significantly faster in V and

VM conditions ($M = 113.16, \mathrm{SE} = 2.87$ and $M = 111.7, \mathrm{SE} = 2.81$ respectively) compared to VA and VAM ($M = 94.12, \mathrm{SE} = 2.57$ and $M = 96.63, \mathrm{SE} = 2.47$ respectively). This indicated that in stormy weather, much like in the sunny weather condition, adding motion cues did not have an effect on the mean speed, while auditory cues resulted in slower speed that was closer to the target speed of 80.

3.2.2 Speed Variability

There was a main effect of sensory condition on speed variability, $F(3,192) = 24.18, p < .0005, \eta_p^2 = .274, \varepsilon = .835$, with standard deviation of speed significantly higher during V and VM conditions ($M = 6.23, \mathrm{SE} = 0.38$ and $M = 6.45, SE = 0.31$ respectively) in comparison to VA and VAM ($M = 4.20, \mathrm{SE} = 0.22$ and $M = 4.25, \mathrm{SE} = 0.29$ respectively). This indicates that auditory cues improved driving performance by reducing the speed variability, but similar to sunny weather, physical motion cues did not.

3.2.3 Acceleration

Sensory condition effected acceleration, $F(3,192) = 16.646, p < .0005, \eta_p^2 = .206$, such that mean absolute value of acceleration was significantly higher in V and VM conditions ($M = 0.403, \mathrm{SE} = 0.020$ and $M = 0.410, \mathrm{SE} = 0.018$ respectively) compared to VA and VAM ($M = 0.321, \mathrm{SE} = 0.017$ and $M = 0.309, \mathrm{SE} = 0.019$ respectively). These findings confirmed that physical motion cues did not have an effect on acceleration, whereas auditory cues reduced acceleration, in both sunny and stormy weather conditions.

3.2.4 Speed of Crossing the Bumps

Speed of crossing the bumps depended on sensory cues present, $F(3,192) = 6.878, p = .001, \eta_p^2 = .097, \varepsilon = .813$. Speed was significantly higher in V and VM conditions, ($M = 34.85, \mathrm{SE} = 3.57\ and\ M = 35.17, \mathrm{SE} = 3.54$) when compared to VAM ($M = 28.44, \mathrm{SE} = 2.68$). There were no significant difference between other pairs of sensory condition, VA ($M = 29.74, \mathrm{SE} = 2.74$). Therefore, presence of auditory cues may improve estimation of speed when crossing the bumps.

3.2.5 Lateral Position

Similar to the sunny weather condition, lateral position was not affected by sensory condition, $F(3,192) = 0.277, p = .842, \eta_p^2 = .004$.

3.2.6 Lateral Position Variability

Participants' deviation from center of the lane varied with sensory condition, $F(3,192) = 15.239, p < .0005, \eta_p^2 = .192, \varepsilon = .753$. Lateral position variability was significantly higher in V condition, ($M = 0.479, \mathrm{SE} = 0.026$) compared to VA, VM and VAM ($M = 0.403, \mathrm{SE} = 0.020, M = 0.402, \mathrm{SE} = 0.019\ and\ M = 0.368, \mathrm{SE} = 0.015$ respectively). Thus, addition of auditory or vestibular cues can reduce variability in lateral position.

3.3 Discussion

Results from mean speed, speed variability, and mean magnitude of acceleration revealed that auditory cues improved individuals' estimation of self-motion speed, as well as their measures of speed control (speed variability and mean acceleration magnitude) compared to visual cues alone. However, the addition of vestibular cues, without auditory, did not have an effect neither on estimation of speed, nor on speed control.

Speed of crossing the bumps was reduced significantly with the addition of each sensory cue, with the smallest values corresponding to the VAM (Visual, Auditory, and Motion) condition, suggesting that when information is available from multiple sensory cues, participants show improved driving control.

Vestibular and auditory cues did not influence mean lateral position. This was expected because in our experiment only visual cues carried information about absolute position relative to the center of the road. However, the addition of auditory or vestibular cues did have a significant impact on reducing lateral position variability (e.g., the extent to which position varied around the mean). This observation differed from Experiment 1 which showed the reduction of lateral position variability for vestibular cues only. We will compare the two experiments in the next section.

4 Comparing Sunny and Stormy Weather Conditions

A comprehensive analyses compared the findings of the sunny and stormy experiments across measures, with weather condition as an independent between-subject variable.

4.1.1 Practice Effects

To evaluate practice effects across the four blocks, we performed a mixed ANOVA on all measures described above, with block number as a within-subject variable and weather condition as a between-subject variable.

Table 1. Summary of the statistical tests on practice and weather on driving performance measures (significant tests are bolded). The Greenhouse–Geisser adjustment for violations of sphericity (as determined by Mauchly's test of sphericity) was applied in all cases where sphericity was violated, in which case epsilon (ε) is reported and the results are presented with original degrees of freedom and adjusted p values.

Measure	Condition	Statistical Test
Speed	Practice	$F(3,393) = 0.742, p = .514, \eta^2 = .006, \varepsilon = .893$
	Weather	$\boldsymbol{F(1,131) = 4.135, p = .044, \eta^2 = .031}$
	Interaction	$F(3,393) = 1.046, p = .367, \eta^2 = .008, \varepsilon = .893$
Speed Variability	**Practice**	$\boldsymbol{F(3,393) = 11.98, p < .0005, \eta^2 = .085, \varepsilon = .909}$
	Weather	$F(1,131) = 0.595, p = .442, \eta^2 = .005$
	Interaction	$F(3,393) = 1.090, p = .350, \eta^2 = .008, \varepsilon = .909$
Acceleration	**Practice**	$\boldsymbol{F(3,393) = 1.090, p < .0005, \eta^2 = .060, \varepsilon = .898}$
	Weather	$\boldsymbol{F(1,131) = 5.474, p = .021, \eta^2 = .041}$
	Interaction	$F(3,393) = 1.369, p = .254, \eta^2 = .011, \varepsilon = .898$
Speed of Crossing Bumps	Practice	$F(3,393) = 1.119, p = .338, \eta^2 = .009, \varepsilon = .885$
	Weather	$\boldsymbol{F(1,131) = 8.958, p = .003, \eta^2 = .065}$
	Interaction	$F(3,393) = 1.613, p = .192, \eta^2 = .012, \varepsilon = .885$
Lateral Position	**Practice**	$\boldsymbol{F(3,393) = 14.92, p < .0005, \eta^2 = .104, \varepsilon = .919}$
	Weather	$\boldsymbol{F(1,131) = 8.953, p = .003, \eta^2 = .065}$
	Interaction	$F(3,393) = 2.193, p = .094, \eta^2 = .017, \varepsilon = .919$
Lateral Position Variability	**Practice**	$\boldsymbol{F(3,393) = 4.986, p = .003, \eta^2 = .037, \varepsilon = .906}$
	Weather	$\boldsymbol{F(1,131) = 44.13, p < .0005, \eta^2 = .255}$
	Interaction	$F(3,393) = 1.987, p = .122, \eta^2 = .015, \varepsilon = .906$

The results indicated that practice had a significant main effect on speed variability, acceleration, lateral position, and lateral position variability. Since the order of sensory cues for each block was counterbalanced, this observation can be attributed to practice effects. Moreover, this effect was not dependent on the weather condition, as none of the interaction terms were significant.

4.1.2 Compare measures

To compare the measures of driving performance between weather conditions, a two-way mixed ANOVA was performed, in which sensory condition was a within-subject variable and weather was a between-subject variable. The results revealed absence of significant main effect of weather condition (sunny or stormy) on speed variability, with $F(1,131) = .771, p = .381, \eta_p^2 = .006$.

However, weather condition had an effect on mean speed, mean acceleration and speed of crossing the bumps, with $F(1,131) = 4.5, \mathrm{p} = .036, \eta_p^2 = .033$, $F(1,131) = 6.08, \mathrm{p} = .015, \eta_p^2 = .045$ and $F(1,131) = 9.124, \mathrm{p} = .003, \eta_p^2 = .066$, respectively. Moreover, looking at the measures of lateral control, there was a significant main effect of weather condition on lateral position and lateral position variability, with $F(1,131) = 10.05, \mathrm{p} = .002, \eta_p^2 = .072$ and $F(1,131) = 24.26, \mathrm{p} < .0005, \eta_p^2 = .157$, respectively. These effects confirm that, except in the case of speed variability, all other driving performance measures were affected by compromised visual cues in the stormy weather condition.

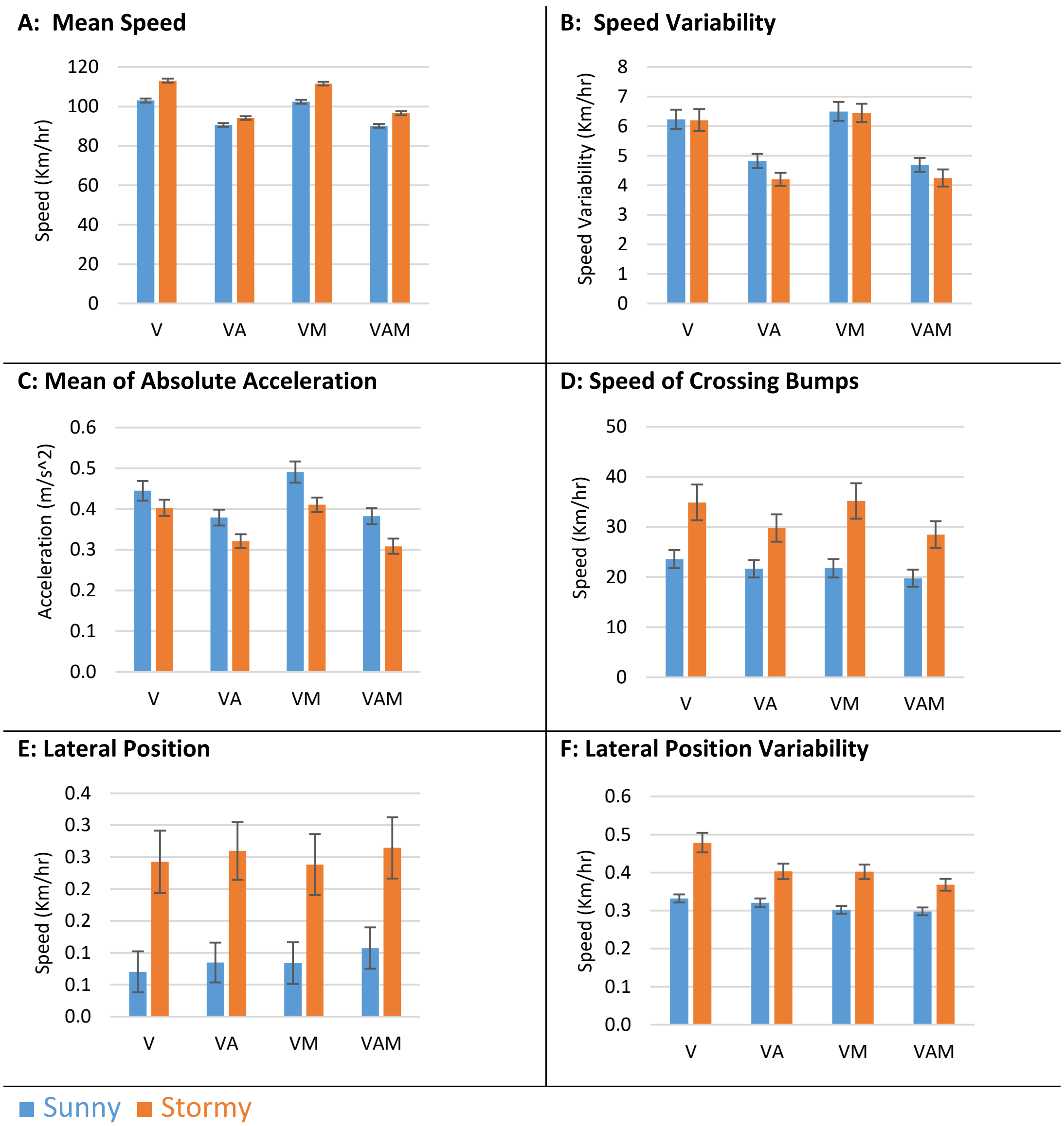


Figure 8. Different Measures of Driving Performance Across Sensory and Weather Conditions. A- Mean Speed. B- Speed Variability. C- Mean of Absolute Acceleration (collapsing over acceleration and deceleration). D- Speed of Crossing the Bumps. E- Mean Lateral Position. F- Lateral Position Variability

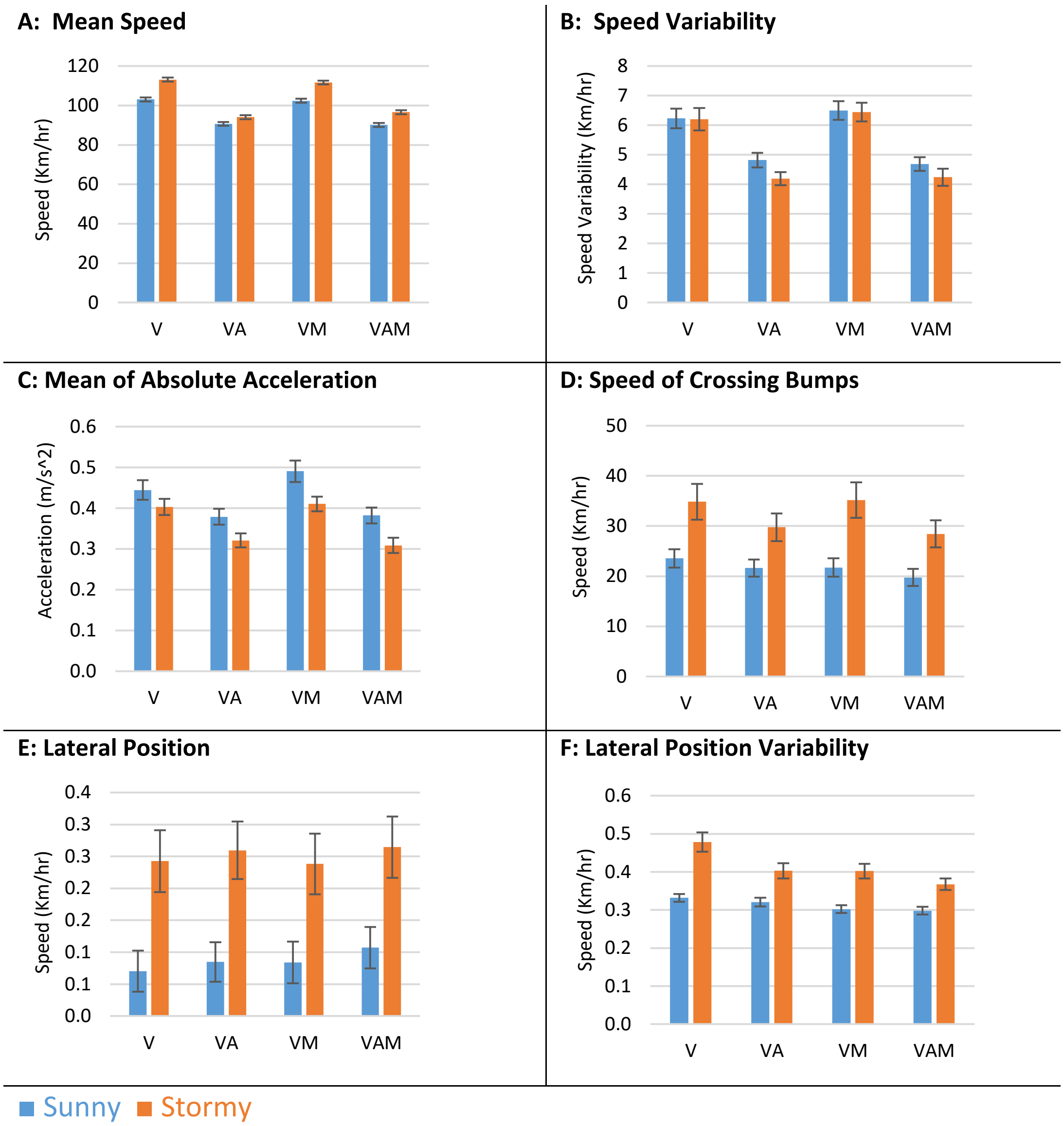


Figure 8 illustrates the differences between measures of performance across weather and sensory conditions. In general participants drove faster in stormy conditions compared to sunny ($p = .005, p = .005, and\ p = 0.030$ for V, VM, and VAM respectively). The only exception was in the case of the VA sensory condition in which no significant differences were observed ($p = 0.151$). These results were potentially interesting since the change seemed to be dependent on presence of the motion cues rather than auditory.

There was a significant reduction in the average of the absolute value of acceleration in VA, VM, and VAM conditions in the stormy weather condition when compared with sunny ($p = .015, p = .006, and\ p = .004$ respectively), but there was no significant difference in the V condition ($p = 0.094$). Therefore, it can be argued that in all multisensory conditions the mean acceleration values were lower in the stormy condition compared to the sunny weather condition.

Participants in stormy weather also crossed the bumps faster in all sensory conditions ($p = .002, p = .006, p < .0005, and\ p = 0.003$ for V, VA, VM, VAM respectively). This suggests that compromised visual cues in the stormy condition significantly diminished participants' ability to see and respond to obstacles such as speed bumps.

When looking at lateral position measures, participants in stormy weather had higher absolute values in all sensory conditions ($p = .002, p = .001\ p = .004, and\ p = 0.003$ for V, VA, VM and VAM respectively). We suggest that stormy conditions made it more difficult to for participants to realize the center of their lane and had a tendency to drive closer to the rails on the right side of the road. Along the same line, we observed an increase in lateral position variability in the stormy condition, with $p < .0005$ for all sensory conditions, confirming the diminished lane control when the visual cues were compromised. However, the addition of auditory or vestibular cues were effective in improving this weakened lane control.

5 General Discussion

During driving, visual information is most often the dominant source of information used to estimate position and speed (Berthoz et al., 1975; Fetsch et al., 2009). However, other sensory systems contribute to self-motion perception. This paper examined the effect of integration of visual, auditory, and vestibular information in forming the perception of self-motion while driving a car. Specifically, we were interested in whether speed and position management while driving are influenced by adding auditory and/or vestibular cues, and how these influences might change when the dominant visual cues are compromised.

We ran two experiments in an immersive virtual environment, using a driving simulator, to observe the effect of vestibular, auditory, and visual information on how well participants controlled the vehicle in terms of speed, acceleration, lateral position, and handling of hazards (speed bumps). In the second experiment, we examined how driving performance changed across the same measures when the visual information was compromised. Specifically, we compared driving in sunny (clear) weather conditions (Experiment 1) with driving in stormy weather conditions (Experiment 2).

Speed profile can reveal extensive information about driving performance, since it has a well-established relationship with safe driving (Aarts & Van Schagen, 2006; Joksch, 1993). For example, velocity influences how much time drivers have to react in various driving scenarios. In our study, drivers underestimated their speed in all four sensory conditions, in both sunny and stormy weather conditions. Notably, providing vestibular cues along with the visual cues did not affect mean speed, but auditory cues did; drivers were more accurate in estimating their speed when auditory cues were present.

Because the vestibular system detects acceleration rather than velocity (Berthoz et al., 1975; Siegle et al., 2009), acceleration is a better measure of the effect of vestibular information on driving control. Speed variability and mean acceleration are both indicators of control over speed. We measured speed variability in terms of standard deviation of speed, which provided a measure of overall variability within a time window. However, it is diagnostic to observe changes in variability within that same time window. We measured acceleration as the instantaneous changes of speed to further distinguish between sudden and gradual changes within the same time window. When we compared speed variability in sunny and stormy (compromised vision) weather conditions, auditory cues reduced the overall variability of speed, however, vestibular cues did not have an effect on speed variability and in fact seemed to reduce the effect of the auditory cue when both were presented. In contrast, the more sensitive measure of absolute acceleration revealed that both vestibular and auditory cues led to improved control over speed in the stormy condition over the sunny and clear condition. These results fit with our expectations, because the output of the dominant (visual) sensory system was unreliable in the stormy weather condition, in which case the vestibular and auditory cues should provide useful information for control of speed.

The observed increase in the speed of crossing the bumps in stormy weather supports the claim that vision was compromised in the stormy weather condition, and that identifying and reacting to speed bumps was harder.

Another important parameter in vehicle control is lateral position, defined as the distance between the center of car and the center of the road. Mean lateral position values indicated that in the sunny weather condition drivers were successful in staying in the center of the lane, but that drivers in the stormy weather condition tended to show a rightward bias. Instructions were clear that participants are supposed to drive in the center of the right lane, therefore in the reduced visibility in the stormy weather, participants might have been overcompensating as they tried to stay in their lane. It is possible that drivers tended to drive closer to the rails on the right side to improve speed information carried by the optic flow of the posts.

Along the same lines, lateral position variability provided a measure of control, as it captures the magnitude of deviation around the mean. In the sunny weather condition, reduced lateral position variability in presence vestibular cues was observed; in other words, drivers appeared to be better able to maintain correct lane position when vestibular cues were available. This effect may well be attributed to the sensitivity of the vestibular system in detecting lateral accelerations. Interestingly, lateral position variability in the second (stormy weather) experiment was affected by not only the vestibular but the auditory cues as well. This was surprising because in our experimental setup the auditory cues did not carry direct information about lateral position. Thus, the effect of auditory information may be attributed to indirect effect of auditory cues on vehicle control. For example, auditory information might have provided the participants with information about speed, and therefore helped them maintain a steadier driving pattern resulting in lower lateral position variability values.

The results of this study showed a consistent effect of auditory cues on improving different measures of driving performance. We suggest that better driving control may be achieved when auditory information is available, particularly when other cues are unreliable.

Notably, addition of vestibular motion cues had a significant effect on only some of the driving performance parameters. For example, vestibular information helped with participants to stay in their lane, and this effect was magnified in stormy weather conditions. More detailed and specific studies on the effect on vestibular cues on driving are necessary.

6 References

Aarts, L., & Van Schagen, I. (2006). Driving speed and the risk of road crashes: A review. *Accident Analysis & Prevention, 38*(2), 215-224.

Angelaki, D. E. (2004). Eyes on target: what neurons must do for the vestibuloocular reflex during linear motion. *Journal of neurophysiology, 92*(1), 20-35.

Angelaki, D. E., & Cullen, K. E. (2008). Vestibular system: the many facets of a multimodal sense. *Annu. Rev. Neurosci., 31*, 125-150.

Benson, A., Spencer, M., & Stott, J. (1986). Thresholds for the detection of the direction of whole-body, linear movement in the horizontal plane. *Aviation, space, and environmental medicine*.

Berthoz, A., Pavard, B., & Young, L. (1975). Perception of linear horizontal self-motion induced by peripheral vision (linearvection) basic characteristics and visual-vestibular interactions. *Experimental brain research, 23*(5), 471-489.

Bremmer, F. (2011). Multisensory space: from eye-movements to self-motion. *The Journal of physiology, 589*(4), 815-823.

Britten, K. H. (2008). Mechanisms of self-motion perception. *Annu. Rev. Neurosci., 31*, 389-410.

Butler, J. S., Smith, S. T., Campos, J. L., & Bülthoff, H. H. (2010). Bayesian integration of visual and vestibular signals for heading. *Journal of vision, 10*(11), 23-23.

Calabro, F., Soto-Faraco, S., & Vaina, L. M. (2011). Acoustic facilitation of object movement detection during self-motion. *Proceedings of the Royal Society of London B: Biological Sciences*, rspb20102757.

Campos, J. L., Butler, J. S., & Bülthoff, H. H. (2012). Multisensory integration in the estimation of walked distances. *Experimental brain research, 218*(4), 551-565.

Cassavaugh, N. D., Domeyer, J. E., & Backs, R. W. (2011). *Lessons learned regarding simulator sickness in older adult drivers.* Paper presented at the International Conference on Universal Access in Human-Computer Interaction.

Conchillo, Á., Recarte, M. Á., Nunes, L., & Ruiz, T. (2006). Comparing speed estimations from a moving vehicle in different traffic scenarios: Absence versus presence of traffic flow. *The Spanish journal of psychology, 9*(1), 32-37.

Cullen, K. E. (2012). The vestibular system: multimodal integration and encoding of self-motion for motor control. *Trends in neurosciences, 35*(3), 185-196.

DeAngelis, G. C., & Angelaki, D. E. (2012). Visual–vestibular integration for self-motion perception.

Denjean, S., Roussarie, V., Kronland-Martinet, R., Ystad, S., & Velay, J.-L. (2012). *How does interior car noise alter driver's perception of motion? Multisensory integration in speed perception.* Paper presented at the Acoustics 2012.

Dichgans, J., & Brandt, T. (1978). Visual-vestibular interaction: Effects on self-motion perception and postural control *Perception* (pp. 755-804): Springer.

Evans, L. (1970). Speed estimation from a moving automobile. *Ergonomics, 13*(2), 219-230.

Fetsch, C. R., Turner, A. H., DeAngelis, G. C., & Angelaki, D. E. (2009). Dynamic reweighting of visual and vestibular cues during self-motion perception. *Journal of Neuroscience, 29*(49), 15601-15612.

Frenz, H., & Lappe, M. (2005). Absolute travel distance from optic flow. *Vision research, 45*(13), 1679-1692.

Godley, S. T., Triggs, T. J., & Fildes, B. N. (2002). Driving simulator validation for speed research. *Accident Analysis & Prevention, 34*(5), 589-600.

Guedry, F. E. (1974). Psychophysics of vestibular sensation *Vestibular System Part 2: Psychophysics, Applied Aspects and General Interpretations* (pp. 3-154): Springer.

Guedry, F. E. (1977). *Visual Counteraction of Nauseogenic and Disorienting Effects of Some Whole-Body Motions--A Proposed Mechanism*. Retrieved from

Horswill, M. S., & McKenna, F. P. (1999). The development, validation, and application of a video-based technique for measuring an everyday risk-taking behavior: Drivers' speed choice. *Journal of Applied psychology, 84*(6), 977.

Horswill, M. S., & Plooy, A. M. (2008). Auditory feedback influences perceived driving speeds. *Perception, 37*(7), 1037-1043.

Joksch, H. C. (1993). Velocity change and fatality risk in a crash—a rule of thumb. *Accident Analysis & Prevention, 25*(1), 103-104.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology, 3*(3), 203-220.

Matthews, M. L., & Cousins, L. R. (1980). The influence of vehicle type on the estimation of velocity while driving. *Ergonomics, 23*(12), 1151-1160.

McLane, R. C., & Wierwille, W. W. (1975). The influence of motion and audio cues on driver performance in an automobile simulator. *Human factors, 17*(5), 488-501.

Merat, N., & Jamson, H. (2011). A driving simulator study to examine the role of vehicle acoustics on drivers' speed perception.

Milošević, S. (1986). Perception of vehicle speed. *Revija za psihologiju*.

Morgan, M. L., DeAngelis, G. C., & Angelaki, D. E. (2008). Multisensory integration in macaque visual cortex depends on cue reliability. *Neuron, 59*(4), 662-673.

Ogata, K., & Yang, Y. (2002). *Modern control engineering* (Vol. 4): Prentice hall India.

Previc, F. H., Varner, D. C., & Gillingham, K. K. (1992). Visual scene effects on the somatogravic illusion. *Aviation, space, and environmental medicine*.

Ramkhalawansingh, R. (2018). *Age-related changes in multisensory self-motion perception.* (PhD), University of Toronto.

Ramkhalawansingh, R., Keshavarz, B., Haycock, B., Shahab, S., & Campos, J. L. (2016). Age Differences in Visual-Auditory Self-Motion Perception during a Simulated Driving Task. *Frontiers in Psychology, 7*(595). doi:10.3389/fpsyg.2016.00595

Ramkhalawansingh, R., Keshavarz, B., Haycock, B., Shahab, S., & Campos, J. L. (2017). Examining the Effect of Age on Visual–Vestibular Self-Motion Perception Using a Driving Paradigm. *Perception, 46*(5), 566-585. doi:10.1177/0301006616675883

Recarte, M. A., & Nunes, L. M. (1996). Perception of speed in an automobile: Estimation and production. *Journal of experimental psychology: applied, 2*(4), 291.

Reed-Jones, R. J., Vallis, L. A., Reed-Jones, J. G., & Trick, L. M. (2008). The relationship between postural stability and virtual environment adaptation. *Neuroscience letters, 435*(3), 204-209.

Rowland, B. A., & Stein, B. E. (2014). A model of the temporal dynamics of multisensory enhancement. *Neuroscience & Biobehavioral Reviews, 41*, 78-84.

Siegle, J. H., Campos, J. L., Mohler, B. J., Loomis, J. M., & Bülthoff, H. H. (2009). Measurement of instantaneous perceived self-motion using continuous pointing. *Experimental brain research, 195*(3), 429-444.

Snowden, R. J., Stimpson, N., & Ruddle, R. A. (1998). Speed perception fogs up as visibility drops. *Nature, 392*(6675), 450.

Stoner, H. A., Fisher, D. L., & Mollenhauer, M. (2011). Simulator and scenario factors influencing simulator sickness.

Telford, L., Howard, I. P., & Ohmi, M. (1995). Heading judgments during active and passive self-motion. *Experimental brain research, 104*(3), 502-510.

Triggs, T. J., & Berenyi, J. S. (1982). Estimation of automobile speed under day and night conditions. *Human factors, 24*(1), 111-114.

Väljamäe, A., Larsson, P., Västfjäll, D., & Kleiner, M. (2008). Sound representing self-motion in virtual environments enhances linear vection. *Presence: Teleoperators and Virtual Environments, 17*(1), 43-56.

Warren Jr, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P., & Sahuc, S. (2001). Optic flow is used to control human walking. *Nature neuroscience, 4*(2), 213.

Warren, W. H., & Hannon, D. J. (1988). Direction of self-motion is perceived from optical flow. *Nature, 336*(6195), 162-163.

Wolfe, J., & Cramer, R. (1970). Illusions of pitch induced by centripetal acceleration. *Aerospace medicine, 41*(10), 1136-1139.

7 Appendix

A further analysis quantified the speed profile based on the transient response characteristics around the speed bumps. Measures were extracted from the speed signal around each speed bump using MATLAB's (The MathWorks, Natick, MA) built in functions (Ogata & Yang, 2002).

7.1 Transient Response Characteristics of Speed Signal

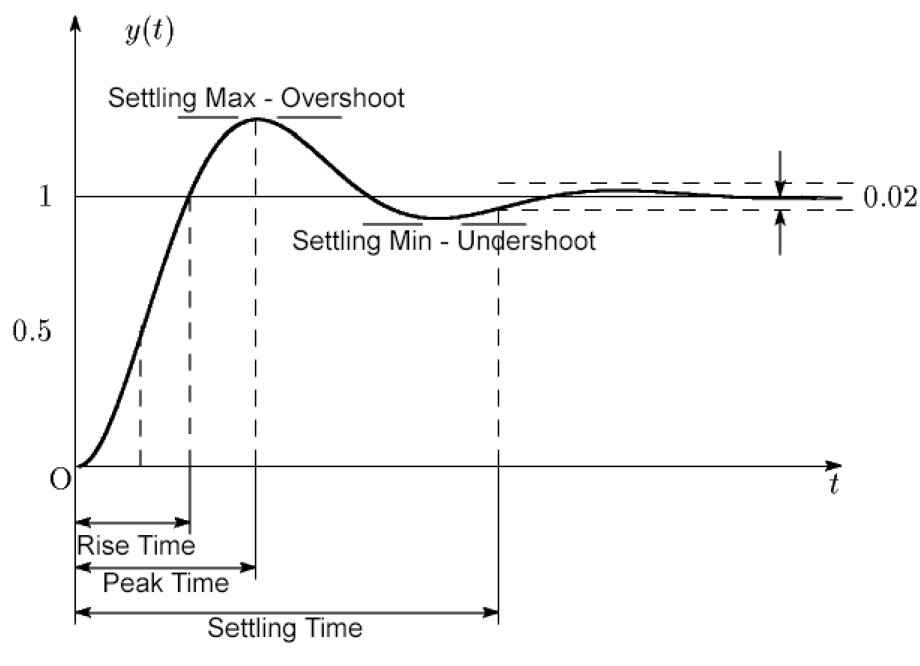
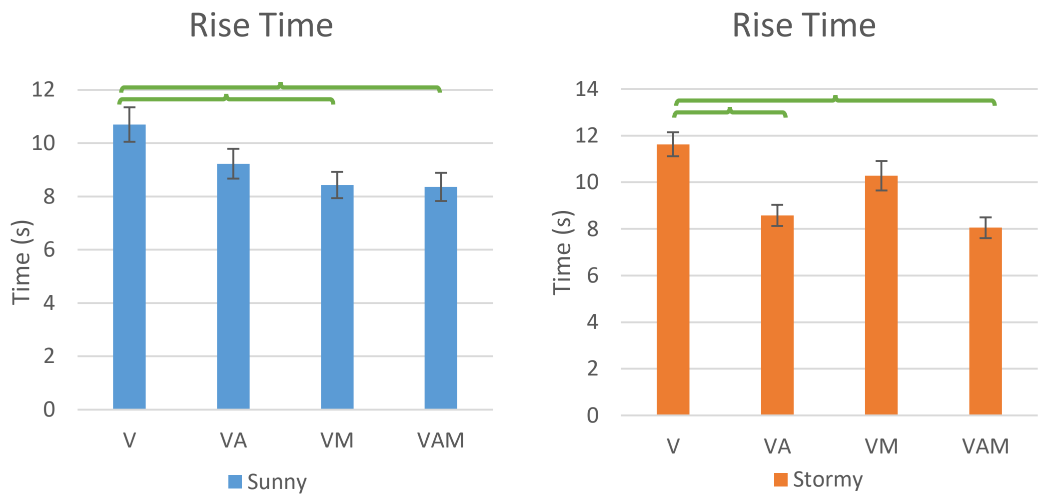
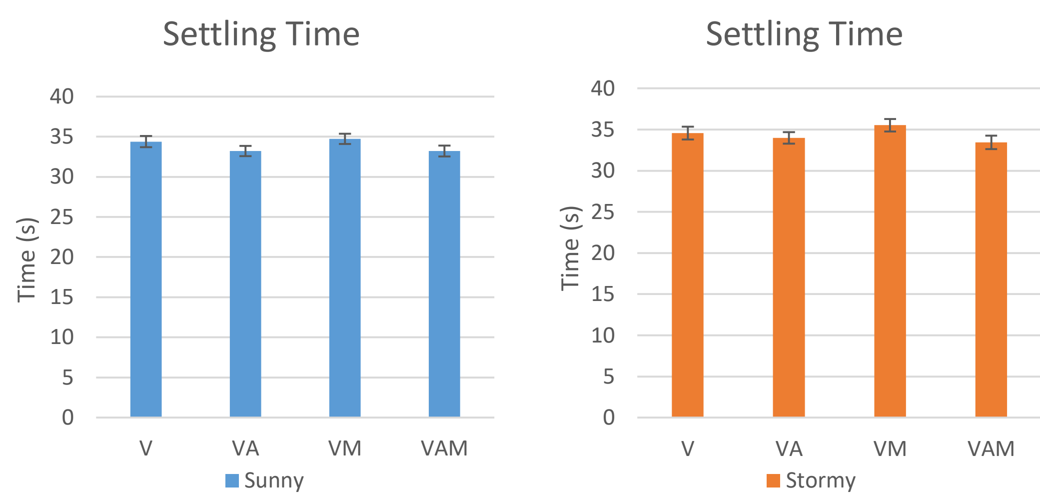


Figure 9. Transient response characteristics on a typical second-order response signal.



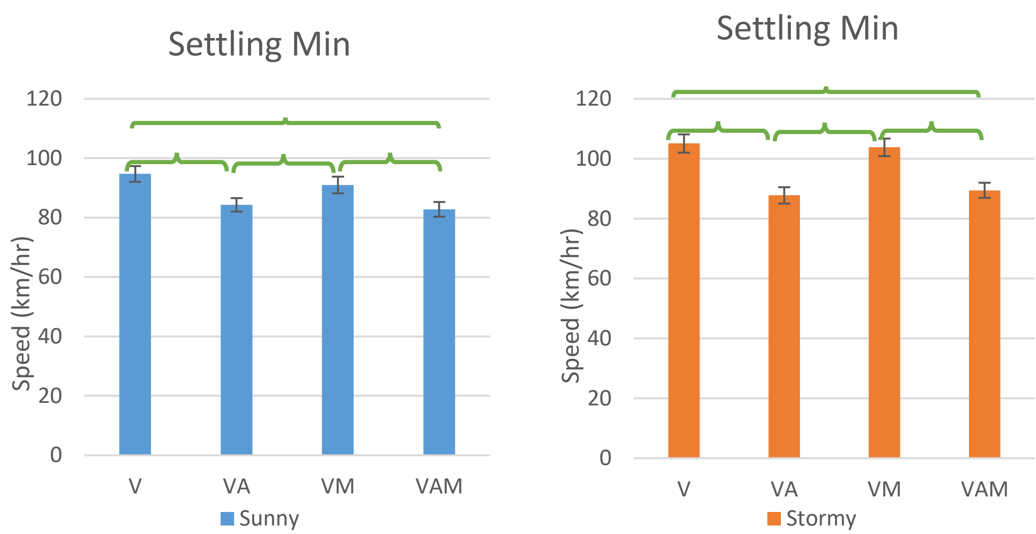
$F(3{,}201) = 9.684, p < .0005, \eta^2 = .126$ $F(2.52{,}161.2) = 15.1, p < .0005, \eta^2 = .191$

Figure 10. Rise time, defined as time it takes for the speed value to rise from 10% to 90% of the steady-state speed, for sunny and stormy weather conditions and the result of repeated measures ANOVA test. Addition of motion cues significantly reduced the rise time for sunny weather, showing a faster approach toward target speed after bumps. The same was observed in auditory cues for stormy condition.



$F(2.672{,}179.0) = 3.157, p = .031, \eta^2 = .045$ $F(3{,}192) = 1.86, p = .137, \eta^2 = .028$

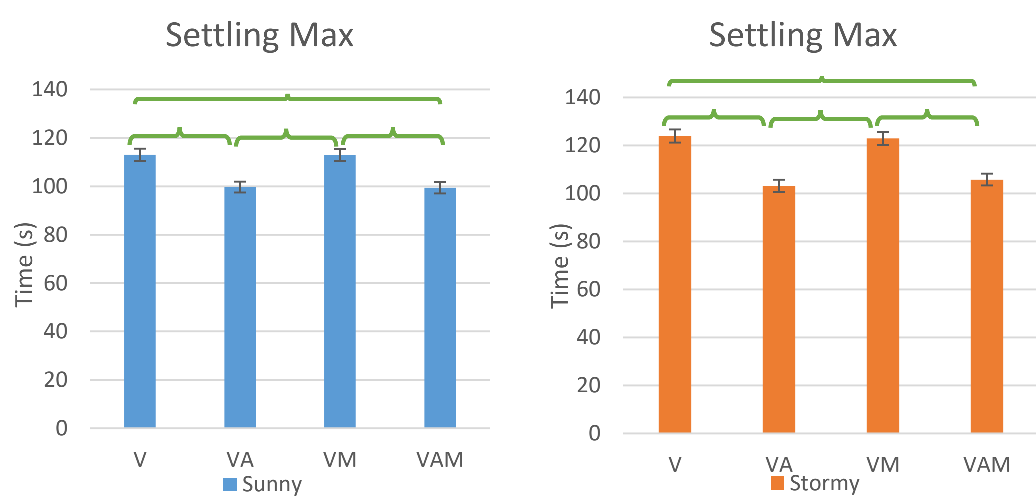
Figure 11. Settling time, time it takes for the speed value from the start point to reach within 2% of the steady-state speed, for sunny and stormy weather conditions and the result of repeated measures ANOVA test. No significant main effect was detected, indicating that there are no differences between how much it takes for participants to reach and maintain their perceived target speed after a speed bump.



$F(2.537,170) = 16.111, p < .0005, \eta^2 = .194$

$F(2.37,151.4) = 39.25, p < .0005, \eta^2 = .380$

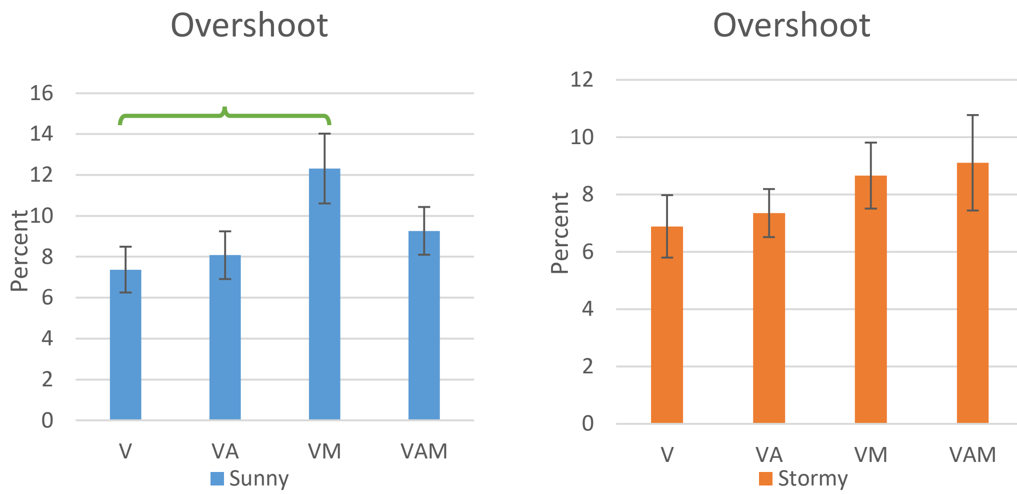
Figure 12. Settling minimum speed (Minimum value of speed after rise time) for sunny and stormy weather conditions and the result of repeated measures ANOVA test. Addition of audio cues significantly reduced the settling minimum speed for both weather conditions, which is a result of slower driving when audio cues are present.



$F(2.485,166.5) = 39.1, p < .0005, \eta^2 = .368$

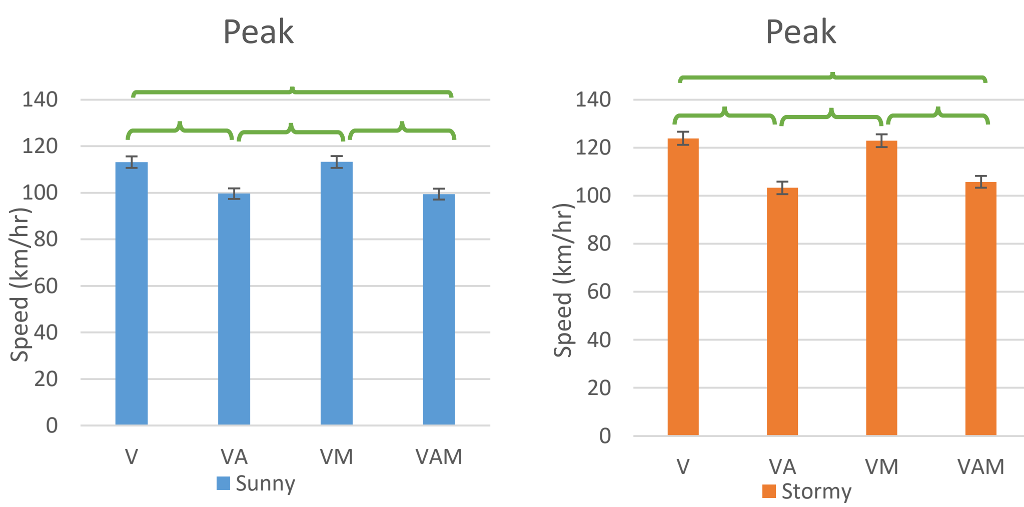
$F(2.487,159.1) = 70.1, p < .0005, \eta^2 = .523$

Figure 13. Settling maximum speed (Maximum value of speed after rise time) for sunny and stormy weather conditions and the result of repeated measures ANOVA test. Addition of audio cues significantly reduced the settling maximum speed for both weather conditions, which is a result of slower driving when audio cues are present.



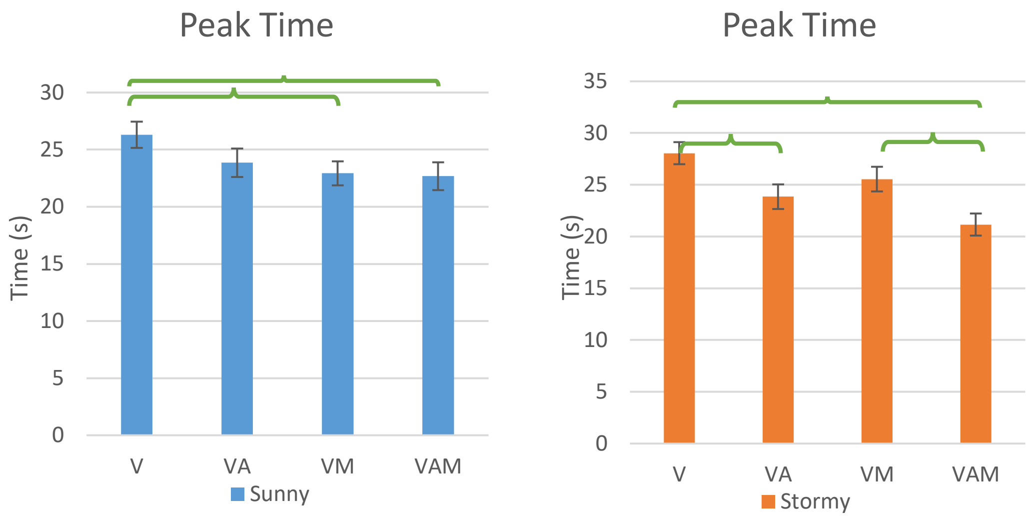
$F(2.395,160.4) = 4.181, p = .012, \eta^2 = .059$ $F(3,192) = 1.183, p = .317, \eta^2 = .018$

Figure 14. Percentage of overshoot ($\frac{Peak\ Speed - Steady\ State\ Speed}{Steady\ State\ Speed}$) *for sunny and stormy weather conditions and the result of repeated measures ANOVA test. Addition of audio cues significantly increase overshoot in sunny weather condition, but only when motion is not present. This finding can be attributed to the difficulty of maintaining a steady speed in presence of feedback from only motion cues.*



$F(2.528,169.4) = 41.7, p < .0005, \eta^2 = .384$ $F(2.45,156.5) = 69.3, p < .0005, \eta^2 = .520$

Figure 15. Peak speed for sunny and stormy weather conditions and the result of repeated measures ANOVA test. Addition of audio cues significantly reduced the peak speed for both weather conditions, which is a result of slower driving when audio cues are present.



$F(2.6,174.17) = 3.550, p = .021, \eta^2 = .050$

$F(3,192) = 9.194, p < .0005, \eta^2 = .126$

Figure 16. Peak time for sunny and stormy weather conditions and the result of repeated measures ANOVA test. Addition of motion cues significantly reduced the peak time for sunny weather conditions, while audio cues did so for stormy weather. In this study, peak time is the time it takes after crossing each bump to reach the maximum speed before the next one.

7.2 Gas and Brake Pedal Position

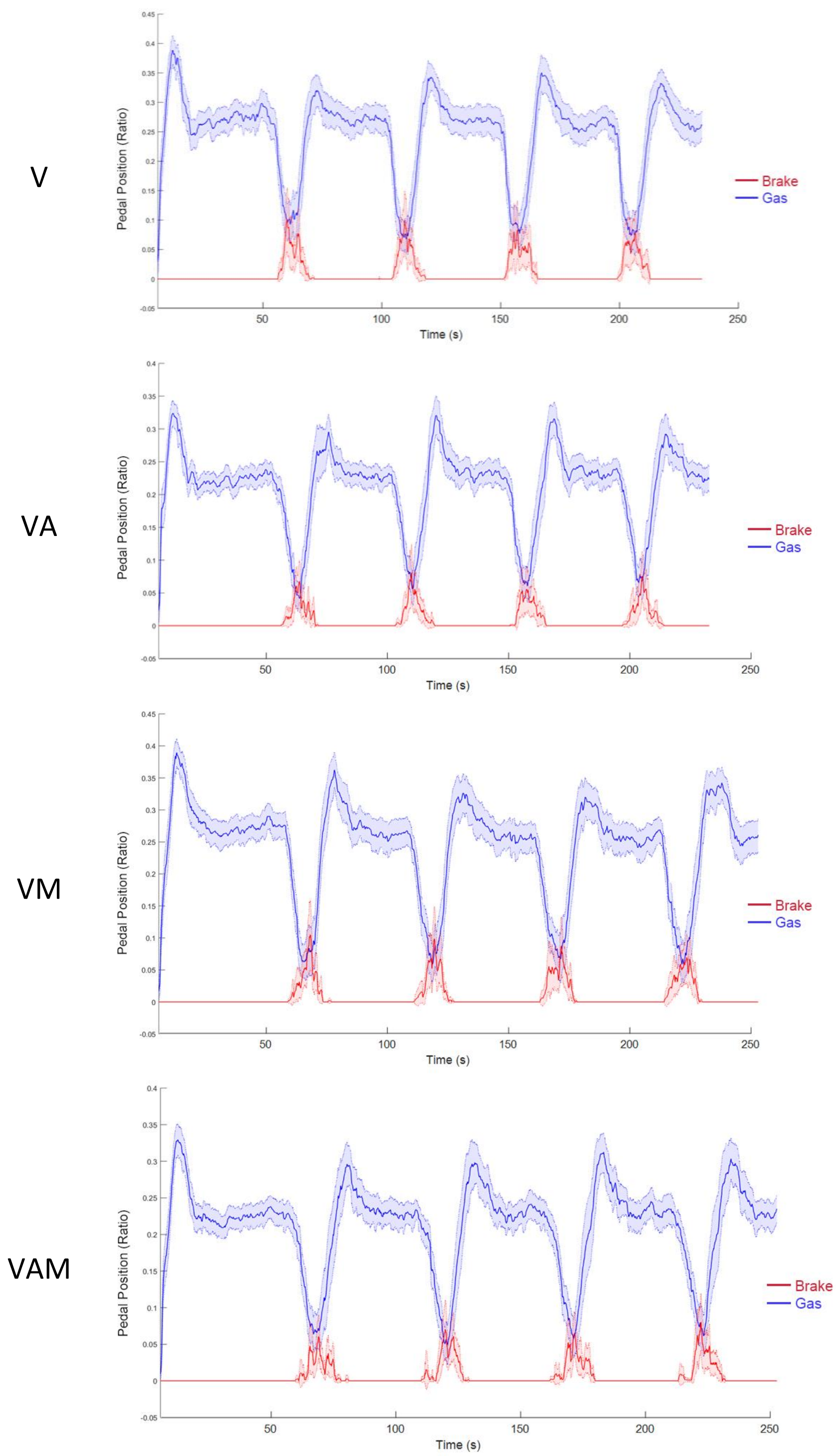


Figure 17. Average position of gas (blue) and brake (red) pedals and their 95% confidence intervals in sunny weather condition.

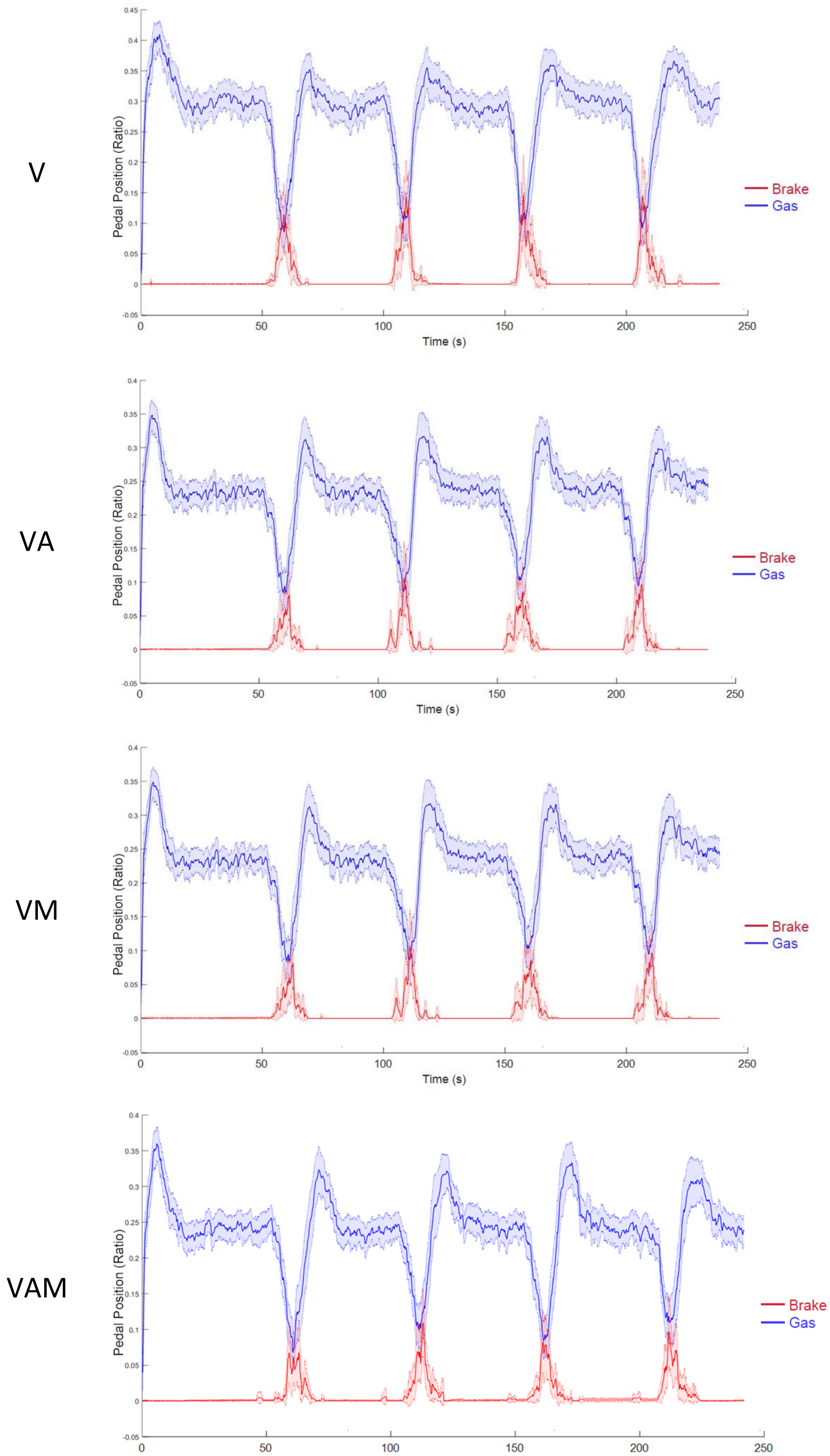


Figure 18. Average position of gas (blue) and brake (red) pedals and their 95% confidence intervals in stormy weather condition.