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ORIGINAL PAPER

A virtual reality evacuation experiment on driving behavior in reduced visibility

Maxine Berthiaume[1,2] · **Arthur Rohaert**[3] · **Max Kinateder**[1,4] · **Enrico Ronchi**[3] · **Noureddine Bénichou**[1]

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Highlights Two visual effects attributed to visibility: loss of contrast and loss of detail.
Smoke and fog density affected headway during driving in virtual reality.
Some participants followed the lead vehicle while others lagged behind.
Limitations of virtual reality could have an impact on driving behavior.

Abstract Understanding human behavior during wildfire evacuations helps to improve the emergency management response. Virtual reality allows to simulate wildfire scenarios that would be challenging or unsafe to recreate in the real-world. Few studies have examined the impact of poor visibility conditions due to smoke on individual and aggregate driving behavior during a wildfire evacuation. This paper presents two studies conducted in virtual reality to better understand the effect of reduced visibility on headway (distance between vehicles). The first study, a pilot study involving 20 participants, investigated how smoke affects visibility using a head-mounted display. Participants' task involved reading out loud the speed limit on a traffic sign placed along the road (no driving required). The results revealed two visual effects that could be attributed to visibility in the virtual environment: the loss of contrast and the loss of detail. Following the pilot study, a driving study involving 51 participants was conducted to examine the impact of lighting conditions (day/night), atmospheric conditions (smoke/fog), and varying density levels of smoke/fog on driving behavior. Participants drove in one atmospheric condition (smoke or fog) during daytime and nighttime through all density levels (random order). The results show that smoke and fog density affected distance headway.

Keywords Driving simulator · Headway · Smoke · Visibility · Wildfire · Evacuation

1 Introduction

Reduced visibility due to smoke during wildfire evacuations can potentially obscure evacuees' visibility on the roads and impact the speeds that evacuees can maintain (e.g., documented during the Camp Fire in California in 2018, Wong et al. 2020). Driving speed and traffic density (which can be obtained through headway, i.e., the distance between vehicles) are two important quantities for traffic simulations (Rohaert et al. 2023a, 2023b). Data from geographical information systems and social networks (e.g., Cova et al. 2024; Kim et al. 2021; Lindell & Prater 2007; Pel et al. 2010a; Sadri et al. 2017; Tamakloe et al. 2021; Wu et al. 2024) can provide useful information on traffic densities or speeds, which can be used to model traffic during an evacuation from a natural hazard. Previous studies have investigated the impact of fog and time of day on driving behavior (e.g., Gao et al. 2020; Kang et al. 2008; Mueller & Trick 2012; Zhu et al. 2016). However, few studies have examined the impact of environmental conditions, such as smoke and light, on driving behavior at the road level in a wildfire context. Controlled empirical studies in simulated environments, such as virtual reality (VR), could provide an opportunity to close this gap. In one study, Wetterberg et al. (2021) investigated individual driving behavior in VR during a wildfire evacuation and found that drivers decreased their speed in conditions of reduced visibility. In a recent study, Rohaert et al. (2025b) examined headways as a function of the speed of a

✉ Maxine Berthiaume
Maxine.Berthiaume@nrc-cnrc.gc.ca

1 National Research Council Canada, Ottawa, Canada

2 School of Psychology, University of Ottawa, Ottawa, Canada

3 Division of Fire Safety Engineering, Lund University, Lund, Sweden

4 Department of Cognitive Science, Carleton University, Ottawa, Canada

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leading vehicle during a wildfire evacuation scenario in VR. The results showed that as visibility worsened, participants reduced their driving speed. However, interestingly, the results suggest that car-following behavior was not significantly affected by poorer visibility: participants maintained a similar distance to the vehicle in front of them (distance headway) regardless of the smoke density. The current study considered the effect of additional environmental conditions on headway: time of day and reduced visibility due to fog. Moreover, Rohaert et al. (2025b) and the current study used different study designs.

Headway is particularly important for evacuation modeling because it directly constrains evacuation flow when traffic is congested, which is common when many evacuees attempt to leave simultaneously. Numerical studies (Tu et al. 2010; Pel et al. 2010b; Rohaert et al. 2025a) have shown that headway has a strong influence on evacuation outcomes as it directly defines the evacuation flow, while other driving behavior parameters, such as free-flow speed and acceleration do not have a significant impact on heavily congested evacuation scenarios. Understanding headway is therefore essential to improve traffic models that can inform emergency authorities in planning for and managing wildfire evacuations.

VR allows the high-fidelity simulation of scenarios in safe and controlled conditions (e.g., to study human behavior in fire, Arias et al. 2021; Kinateder et al. 2014, wildfire evacuation preparedness and decision-making, Molan & Weber 2021; Molan et al. 2023, wildfire firefighting, Heyao & Tetsuro 2021). In the context of studying the impact of reduced visibility on driving behavior, VR provides detailed information on the visibility conditions at the driver level, which are more difficult to obtain in real-world scenarios. Previous research suggests that VR driving simulators are a valid alternative to real-world driving when examining driving behaviors such as speed (Hartfiel & Stark 2021), headways (Risto & Martens 2014), and gap acceptance (Rossi et al. 2020).

Two indicators that relate to visibility in fire smoke need to be differentiated: visibility itself and the extinction coefficient. Visibility, as a distance, refers to how far a person can see or the distance at which objects become visible (Fridolf et al. 2019). It indicates the clarity of vision in a given environment. In the case of wildfires, visibility is crucial for evacuees who need to navigate through smoke to reach safety. The extinction coefficient, often denoted as K, is a measure of how a substance or medium attenuates and scatters light as it passes through (Mulholland 1995). Higher values of the extinction coefficient K indicate a greater reduction in transmitted light, making the smoke opaquer and hindering visibility: more smoke particles scatter and absorb light, significantly diminishing the amount of light reaching the observer's eyes.

Few studies have examined the impact of smoke on visibility and how environmental conditions influence individual and aggregate driving behavior during a wildfire evacuation. This paper presents two studies: (1) a pilot VR study on visibility and (2) a main VR driving study conducted in Canada. The *pilot study* aimed to understand how smoke affects visibility (i.e., how far one can see) in the virtual environment. The results from the pilot study helped to inform the design and interpret the results of the main driving study. The *main driving study* aimed to better understand the effect of lighting conditions, atmospheric conditions, and varying density levels of smoke or fog on driving behavior (i.e., headway).

2 Pilot study on visibility

Both the pilot study and the main driving study were approved by the National Research Council of Canada's Research Ethics Board under protocol #2023–63. All participants signed an informed consent form prior to taking part in the studies. Both studies were also pre-registered on AsPredicted (https://aspredicted.org/): #139,807 (pilot study) and #143,766 (main study).

The objectives of the pilot study included examining (1) how varying extinction coefficients in a virtual environment affect visibility and (2) the visibility difference in the scenarios used in the main driving study. For additional details about the pilot study, including hypotheses and full methods and results, see the report by Ronchi et al. (2024).

A convenience sample of 20 participants recruited from the National Research Council of Canada took part in the pilot study. Participants were immersed in the virtual environment (without sound) via a Vive Pro Eye head-mounted display (see Sect. 3.1.2 for the hardware specifications). Participants sat in the driver's seat of a virtual car (see Fig. 1) and remained stationary (i.e., no driving). Their task was to read aloud the speed limit on a traffic sign, which was placed at varying distances on the side of the road in accordance with the bisection method. Each trial had a different smoke density, ranging from K = 0.003 to 1.00 m^{-1}. The order of the trials was randomized. Screenshots of the trials are presented in Fig. 2 (note that there were no vehicles in the pilot study). After the trials, participants completed the Snellen visual acuity test (Snellen 1862) and a questionnaire, which inquired about participants' age, gender, visual impairments, and visual acuity scores obtained from the Snellen visual acuity test.

The results from a mixed linear model analysis indicated a strong negative relationship between extinction coefficient

Fig. 1 Photo of a researcher wearing the VR equipment

and visibility. In other words, visibility was worse in the night scenario. The results also showed that two main visual effects can be attributed to the visibility in the virtual environment: the loss of contrast and the loss of detail. Specifically, the visibility will be limited due to the finite resolution of the head-mounted display. The full results from the mixed linear model can be found in the report by Ronchi et al. (2024).

The findings from the pilot study served as a foundation for the main driving study. The visibility derived from the pilot study helps understanding car-following behavior, as the idea of headway only makes sense when participants are able to see the car ahead of them. However, it is important to note that the translation from controlled pilot conditions to dynamic driving scenarios introduces additional complexities that may affect the generalizability of the results. In addition, the visibility measured as the readability of a traffic sign in the pilot study does not translate directly to the visibility of the lead vehicle in the main study (e.g., size and shape of the sign versus the vehicle, dynamic movement of the vehicle, background contrast), which may also impact the generalizability of the findings.

The objective of the main driving study was to understand the effect of lighting conditions (day/night), atmospheric conditions (white fog/orange smoke), and varying fog/smoke density levels on driving behavior.

The research team put forward the following hypotheses[1]:

1. Participants will maintain a larger headway during nighttime than during daytime (based on Zhu et al. 2016).
2. Participants will maintain a larger headway in conditions with a high density of smoke or fog than in conditions with a low density of smoke or fog (based on Intini et al. 2022).

[1] The research team initially hypothesized that participants would drive faster (1) during daytime than during nighttime and (2) in conditions with a low density of smoke or fog than in conditions with a high density of smoke or fog (see Ronchi et al. 2024). However, the study did not test these hypotheses as the lead vehicle capped participants' driving speed (see Sect. 5 Discussion for details).

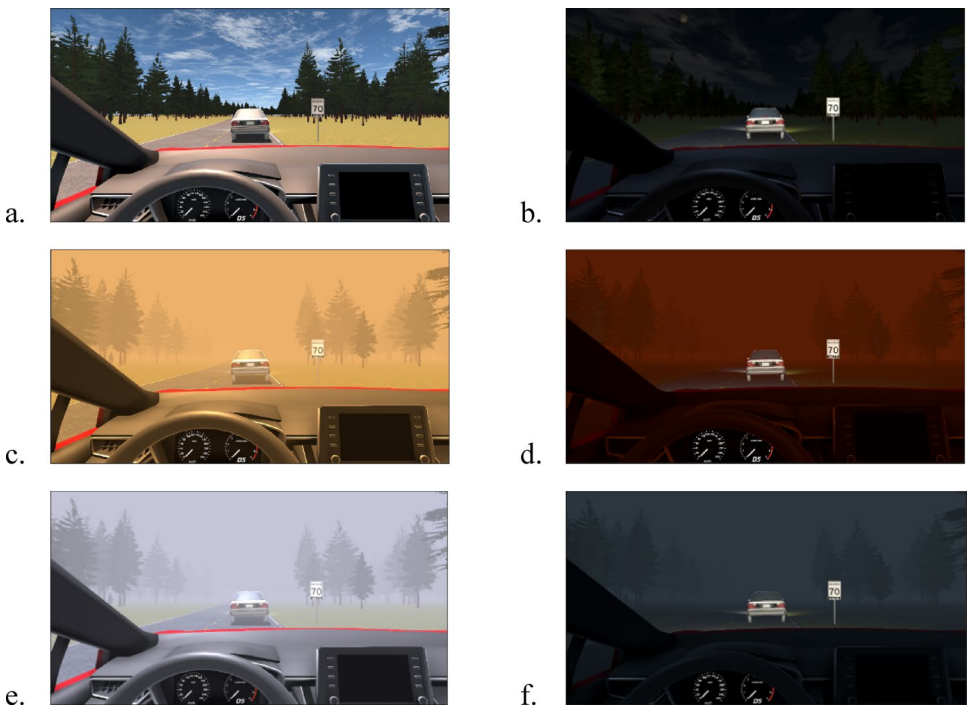

Fig. 2 Illustration of the participant's view in each condition in the studies. The virtual environment for the pilot study did not contain a lead vehicle. **a** day – clear sky scenario; **b** night – clear sky scenario; **c** day – smoke scenario with Unity fog; **d** night – smoke scenario with Unity fog; **e** day – fog scenario with Unity fog; **f** night – fog scenario with Unity fog

3 Methods

3.1 Participants

A convenience sample of 51 participants recruited from the National Research Council of Canada took part in the main study. Note that one or two participants took part in both the pilot study and the main driving study. A power analysis was performed prior to beginning data collection using the software *G*Power* (F-tests; repeated-measures, within-between interaction; a priori; effect size = 0.20; α err prob = 0.05; power (1-β err prob) = 0.95; number of groups = 2; number of measurements = 10; correlation among repeated-measures = 0.5; nonsphericity correction ε = 1; total recommended sample size = 32).

3.2 VR equipment

Participants were immersed in the virtual environment via a Vive Pro Eye head-mounted display (screen: dual OLED 3.5″ diagonal, resolution: 1440 × 1600 pixels per eye, refresh rate: 90 Hz, FOV: 110 degrees). Two Vive SteamVR Base Stations 2.0 tracked participants' position. An HP computer ran the virtual environment (Windows 10, Intel® Xeon® Silver 4114 processor, CPU @ 2.20 GHz 2.19 GHz (2 processors), 96.0 GB RAM) with an NVIDIA graphics card (NVIDIA® GeForce RTX 2080). Participants were seated in a car seat mock-up, which included a Toyota Corolla car seat and a Thrustmaster 300RS steering wheel and acceleration and brake floor pedals to navigate in the driving scenario (see Fig. 1). Participants filled out an online questionnaire on a second computer in the laboratory before and after the VR experiment.

3.3 VR driving scenarios

During the study, three independent variables were manipulated:

- Lighting conditions (day versus night);
- Atmospheric conditions (smoke versus fog); and
- Five levels of smoke and fog obtained by adjusting the extinction coefficient K, based on the results from the pilot study: no smoke ($K = 0.003\ m^{-1}$), low smoke ($K = 0.05\ m^{-1}$), medium smoke ($K = 0.10\ m^{-1}$), high smoke ($K = 0.20\ m^{-1}$), and very high smoke ($K = 0.40\ m^{-1}$).

All participants were randomly assigned to one atmospheric condition: either the smoke or the fog condition. Regardless of the assigned atmospheric condition, all participants drove through both lighting conditions (i.e., day and night). In other words, each participant experienced both lighting conditions (i.e., day and night) but only one atmospheric condition (i.e., smoke or fog). The order of the lighting conditions (day and night) and the five levels of visibility (depending on the assigned atmospheric condition) were presented in a random order. Participants first completed a practice trial to familiarize themselves with the equipment (1 trial), followed by ten experimental trials in the assigned atmospheric condition (5 trials in each lighting condition). For example, if a participant was randomly assigned to the smoke condition, daytime first, they first drove through the practice trial (1 trial), followed by the five levels of smoke in daytime (5 trials, random order) and the same five levels of smoke in nighttime (5 trials, random order). The research team decided to have participants complete only the smoke or the fog condition (instead of both conditions) to minimize cybersickness. Note that exposing participants to only one condition may affect between-group comparisons, as it limits the ability to control for individual differences across conditions.

The VR driving scenarios were developed using Unity version 2020.3.141f. The same settings as the pilot study were used for the smoke and fog (see Appendix 1). Note that there were no streetlamps in the night scenarios. In all trials, participants were the driver (no passengers) and viewed the scenario from a first-person perspective (see Fig. 2 for an illustration). The scenarios did not contain any visual effects other than fog or smoke (e.g., no ember showers or flames).

The practice trial took place during the day in a clear sky scenario on the same highway as the experimental trials. The highway was a two-lane road (one lane in each direction). Each lane was approximately 3 m in width. There were no other vehicles in the trials. The highway was mostly straight and was flat to minimize the cybersickness symptoms of participants. The speed limit was 70 km/h. The road did not have any intersections, stop signs, or traffic lights. There were trees on either side of the road to simulate driving through a forest. Participants were asked to follow the car in front of them (i.e., the lead vehicle was controlled by a waypoint system) without passing or overtaking it, but no other specific actions to follow were presented. When the trial began, the lead vehicle was approximately 15 m in front of the participant. Through the first 50 s of the experiment, the speed of the lead vehicle increased linearly from 10.8 km/h (3 m/s) to 64.8 km/h (18 m/s), meaning that the constant acceleration equaled 0.3 m/s^2. The lead vehicle then maintained a constant speed (64.8 km/h) for 20 s before the experiment ended. Once participants reached the end of the road, the trial ended, and the application stopped automatically.

Participants' task in the baseline and experimental trials was identical to the practice trial. Note that both the practice and baseline trials took place in the day – clear sky scenario.

Once a trial ended, participants were teleported back to the starting position to begin the next trial. The time of day and environmental conditions (i.e., smoke versus fog and level of visibility) varied depending on the assigned atmospheric condition. The Unity application generated an output file with timestamps, the trial number, the trial name and the position, speed, and distance headway of the car driven by the participant. Once participants completed all trials, the application stopped automatically.

3.4 Procedure

When participants arrived for the in-person appointment, a researcher greeted them and briefly explained the study's session procedure (see Fig. 3 for an illustration of the data collection process). Participants were then given time to read and sign the informed consent form. The researcher answered any questions posed by participants. Participants then filled out pre-experiment online questionnaires: the background questionnaire and the Virtual Reality Sickness Questionnaire (VRSQ, Kim et al. 2018; to assess cybersickness).

Once participants finished filling out the questionnaires, the researcher explained the equipment and participants' task in VR (see Fig. 3 for an illustration of the process). The researcher also explained that participants might experience cybersickness and asked them to inform the researcher if this occurred. The researcher then asked participants if they had any questions or concerns and reiterated that participants could choose to stop the study at any time for any reason. Once participants confirmed being ready to begin the experiment, the researcher asked participants to sit in the car seat mock-up and put on the VR headset. Participants completed the practice trial followed by two experimental blocks: Block 1 (smoke or fog, with day or night) and Block 2 (the same atmospheric condition as Block 1, but with the remaining lighting condition), with a break outside of VR between blocks. For example, if a participant was randomly assigned to the smoke condition, daytime first, during Block 1, the participant drove through the five levels of smoke during daytime. During Block 2, they drove through the five levels of smoke during nighttime.

Once all the blocks were completed, participants filled out post-experiment questionnaires: driving scenario, usability, presence, cybersickness (VRSQ), and feedback survey (see Appendix 2 for a full list of measures used). The researcher then verbally debriefed participants to tell them more about the objectives of the study and answer any questions they had.

4 Results

Fifty-one participants took part in the study (smoke condition = 27; fog condition = 24). However, 11 participants were unable to complete the VR experiment due to cybersickness ($n = 9$), going off-road ($n = 1$), and technical issues ($n = 1$). The analysis of the driving data (headway) included all completed driving trials, leading to a total of 423 trials. The analysis of the pre-experiment questionnaires included all available data ($n = 51$). The analysis of the post-experiment questionnaires only included the data of participants who completed most of the VR experiment ($n = 44$) as the questions could only be answered if participants completed the driving scenario.

4.1 Driving behavior data

Not all participants followed the lead vehicle. It is assumed that the participants were only following the car in front of them when they drove the same speed and were still able to see the car. Therefore, two criteria were used to determine if a participant was following during the last twenty seconds of the trial:

1) Speed criterion: $17m/s < \text{avg}\,(v) < 19m/s$

The average speed $\text{avg}\,(v)$ of the participant lies between 17 m/s (61.2 km/h) and 19 m/s(68.4 km/h). This means that the difference in average speed is less than 1 m/s (3.6 km/h) and that the distance headway does not increase or decrease by more than 20 m during the 20-s interval.

2) Visibility criterion: $\min\,(h) < 6.24/K + 4.5m$

The minimum gap (distance headway h minus the car length of 4.5 m) is smaller than the distance at which all contrast is lost, and all pixels look the same. Here, the

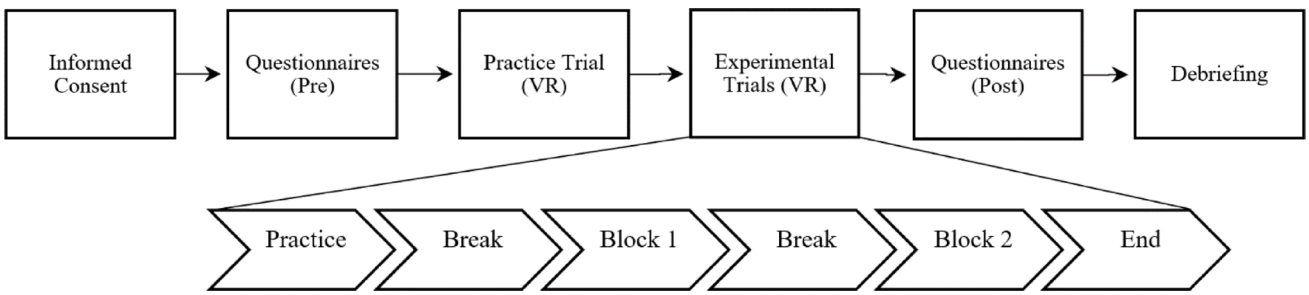

Fig. 3 Illustration of the data collection process for the study

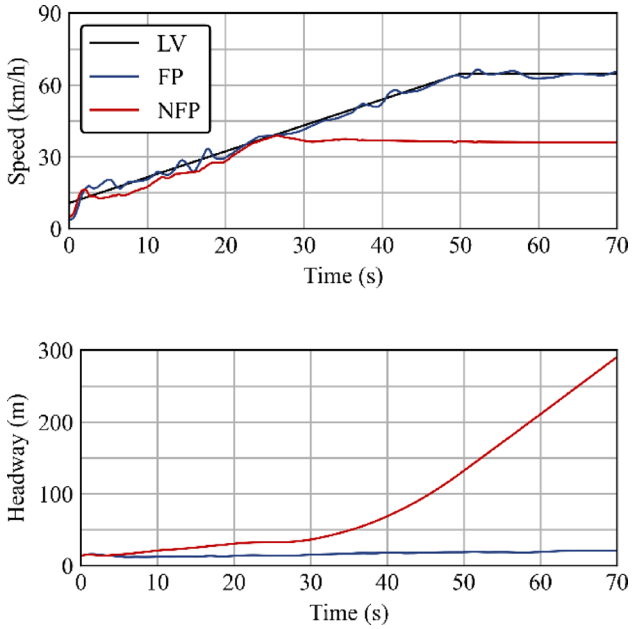

Fig. 4 Speed (left) and distance headway (right) of two participants: one following participant (FP) in blue and one not-following participant (NFP) in red. For reference, the leading vehicle (LV) is shown in black on the speed graph. The participant that does not follow drives consistently slower than the leading vehicle, which leads to a steadily increasing headway

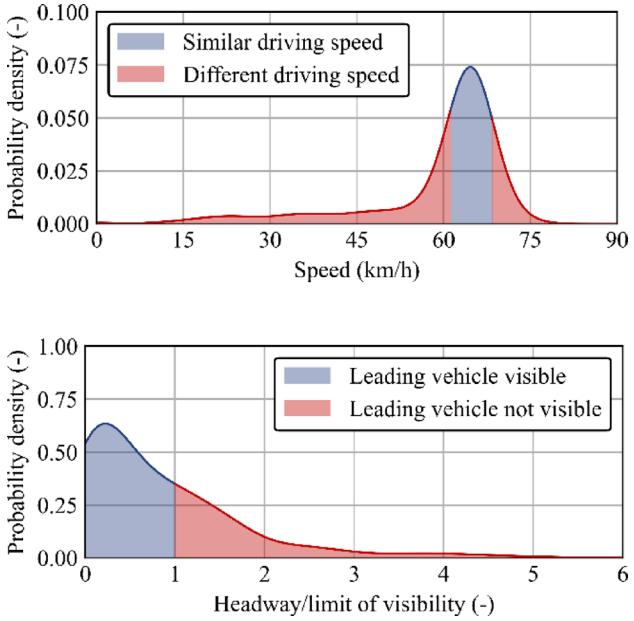

Fig. 5 Distributions of speed and headway. The blue color of the graph on the left indicates participants who drove a similar speed as the lead vehicle. On the right graph, the headway is scaled by the visibility limit. The blue color indicates participants who maintained a headway within the limit of visibility

Table 1 Confusion matrix showing number of trials in which headway and speed criteria were (not) met

		Speed criterion	
		Met	Not Met
Visibility criterion	Met	240 (57%)	49 (12%)
	Not met	56 (13%)	78 (18%)

minimum headway during the 20-s interval was chosen, rather than the average headway. This is because some participants chose to keep the lead vehicle on "the edge of their visible field", decreasing speed when the car was visible and increasing speed when the car became invisible.

Figure 4 visualizes the speed and headway of a participant who follows the leading vehicle and one that does not.

Figure 5 shows the distributions of minimum headway and speed. The overlap between both criteria is presented in Table 1. In total, 423 trials are considered. For 356 (75%) of these completed trials, both criteria were met or not met. For the remaining 105 (25%) of the trials, one criterion was met and the other was not.

Figure 6 presents the proportion of trials in which the "following" criterion was met for the experimental conditions. Between the "Day" and "Night" scenarios, there was no visible difference. The following percentage appears to be 10% higher for the "Fog" trials compared to the "Smoke" trials. The following behavior also varied substantially with the visibility in the trial. 90% of the participants followed in the trials without smoke or fog ($K = 0.003$ m^{-1}), while only 26% of the participants followed when smoke or fog was thin ($K = 0.05$ m^{-1}). Interestingly, and somewhat unexpectedly, for thicker smoke or fog, the percentage of following participants increased again. The last graph in Fig. 6 shows that participants were more likely to follow during the last five trials they completed. Repeated trials may introduce learning effects. However, participants completed the trials in a randomized order, which mitigated these effects.

To assess the statistical significance of the observed differences in participants' following behavior, three two-tailed chi-squared tests were conducted. A Bonferroni correction was applied to the significance threshold to correct for multiple testing ($\alpha_{cor} = \alpha/3 = 0.05/3$). Table 2 summarizes the statistics and p values. The tests revealed no significant difference between "Day" and "Night" scenarios or between "Fog" and "Smoke" conditions, but a significant effect of the extinction coefficient.

Figure 7 presents the headway for different categories. Descriptively, the headway does not seem to differ between the day and night scenarios. It also seems to be similar for the smoke and the fog scenarios, although the probability distribution is wider for the fog scenario, indicating that participants' headways varied more.

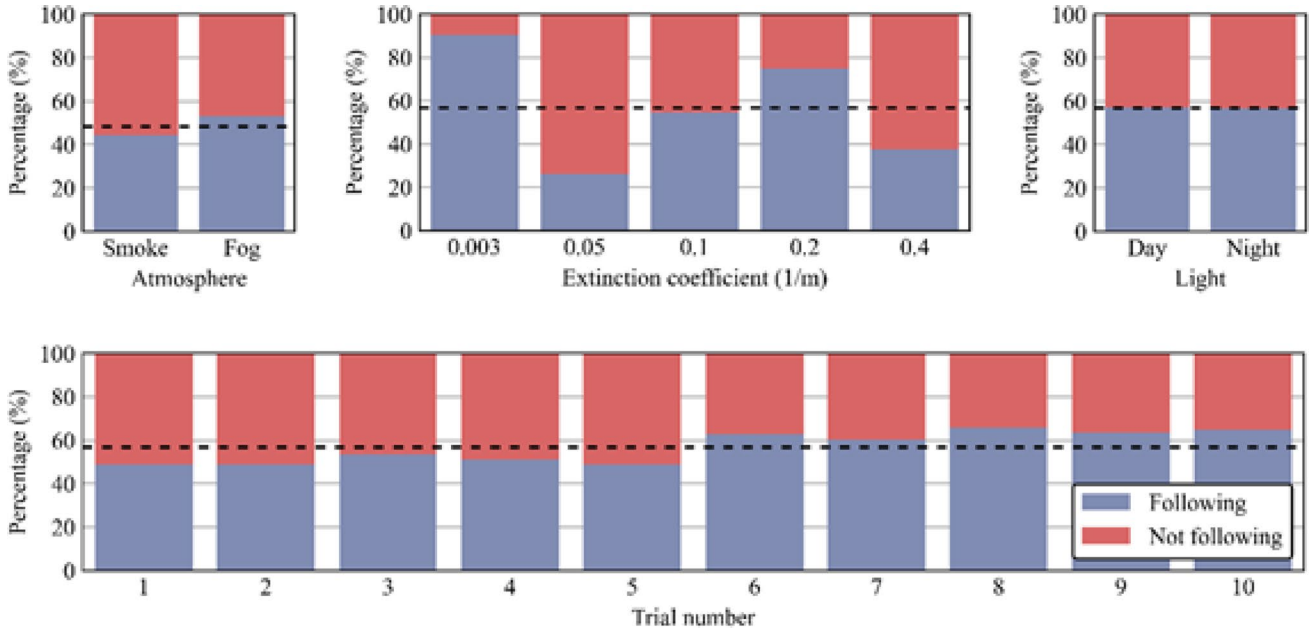

Fig. 6 Following ratio (percentage of trials in which participants follow the lead vehicle) across experimental conditions. The black dotted line presents the average following ratio across all trials (57%). For the second plot, the headways with an extinction factor equal to 0.003 are omitted (because the "no fog" is identical to the "no smoke" trial)

Table 2 Chi-squared statistics and probability values. *For the atmospheric conditions, the scenario without fog/smoke ($K = 0.003$) is not included in the test. Therefore, only 339 trials are considered. For the light conditions and the extinction coefficient, all 423 trials are considered

	Degrees of Freedom	Chi-squared Value	Probability of the hypothesis (p value)
Light conditions	1	0.00	1.000
Atmospheric conditions*	1	2.55	0.110
Extinction coefficient	**4**	**95.07**	**0.000**

The extinction coefficient had a statistically significant effect on the headway: the average distance headway increased with decreasing visibility (see Table 2). However, for the scenario with no smoke/fog ($K = 0.003$/m), the headway was greatest (see Fig. 7). Note that in this scenario, most participants followed. Participants who kept large headways might not have followed in the scenarios with decreased visibility, leading to a bias in the data. Furthermore, individual variability within each visibility condition was notable, with some participants keeping minimal headway regardless of visibility. Thus, while the overall effect of extinction coefficient reached statistical significance, the mean distance headways across conditions were similar, suggesting no consistent trend (see Fig. 7 for the mean distance headway of each extinction coefficient).

The effect of the light conditions (day and night), atmospheric conditions (fog and smoke), and the extinction factor on the distance headway is quantified using a mixed-effects

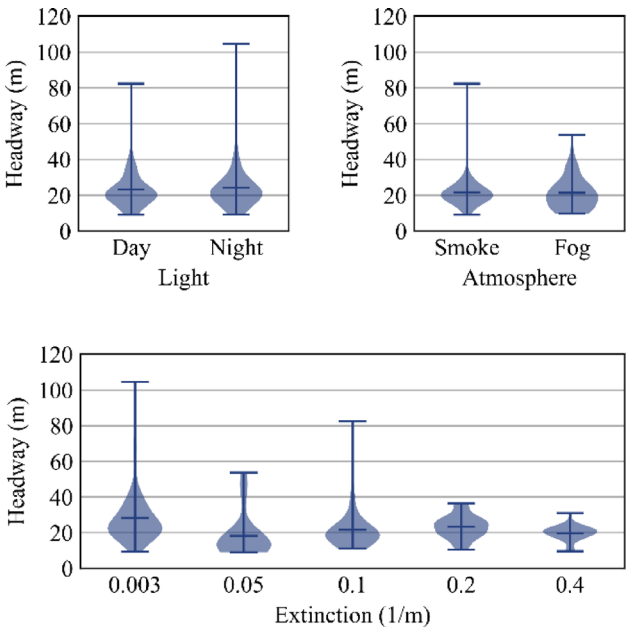

Fig. 7 Violin plots of the distance headway for different categories. The bars indicate the extrema and the mean value. For the middle plot, the headways with an extinction factor equal to 0.003 are omitted (because the "no fog" is identical to the "no smoke" trial)

model. In this analysis, 240 observations across 42 participants were included, with an average of 5.7 observations per participant. Here, the extinction coefficient was considered a categorical variable, as the effect of the extinction on the headway did not appear to be monotone. The model was fitted using the Restricted Maximum Likelihood (REML)

method as implemented in the Python package *Statsmodels* (Seabold & Perktold 2010). A random intercept for each participant and a diagonal covariance structure were used to estimate fixed effects at the population level, while accounting for individual differences in baseline headway through uncorrelated participant-level intercepts. The model successfully converged, indicating reliable results. The results of the MEM analysis, as presented in Table 3, revealed that only the extinction coefficient significantly influenced the headway, with reduced visibility (from low to high smoke) leading to decreased headway distances. This suggests that participants adjusted their behavior based on visibility. The lighting condition (day/night) and atmospheric condition (smoke/fog) did not have a significant effect on headway distances.

4.2 Self-report data

Participants filled out online questionnaires before and after the VR experiment. The results from the analyses relevant to the study objective and hypotheses are presented below. Additional tables and figures are presented in Appendix 3.

A descriptive analysis of the background data of all 51 participants (see Appendix 3 for detailed results) showed that most participants had their driver's license for over 10 years (92.16%), drove on a daily basis (82.35%), owned a car (94.12%), and gained most of their driving experience in Canada (98.04%). Most participants had some experience playing video games (88.23%), but fewer had experience using VR (52.94%). Four participants (7.84%) had previous experience with wildfires (evacuation or fire suppression). Participants were between the ages of 24 and 66 years old (M = 40.41, SD = 9.79). Gender was balanced (women = 26, men = 25). Nine participants withdrew from the study due to cybersickness (17.65% of the sample).

4.3 Driving scenario

Participants' ratings from the driving scenario questionnaire ranged from -3 to 3. A descriptive analysis showed that mean participant ratings were neutral or slightly positive. The item "Perceived risk" had the highest mean rating (M = 1.39, SD = 1.53). The item "Vehicle handling" had the lowest mean rating (M = -0.39, SD = 1.43). See Fig. 8 and Fig. 9 for individual and mean ratings from the driving scenario questionnaire.

4.4 Cybersickness

Cybersickness was assessed using the Virtual Reality Sickness Questionnaire (VRSQ). Two subscale scores (Oculomotor and Disorientation) and a total score were computed for this questionnaire. The results from the descriptive analysis suggested that cybersickness increased over time. One outlier was identified by visually inspecting the data. The means of both subscales and the total score were higher when the outlier was included in the computation than when it was excluded (see Table 4). Paired samples t-tests (see Appendix 3) showed that the difference between mean cybersickness scores before and after the VR experiment was significant for both the smoke and the fog conditions.

4.5 Open-ended feedback

Open-ended feedback collected from participants was analyzed by identifying patterns in participants' comments. In terms of variables that affected speed choice, many participants noted that visibility affected the speed at which they were comfortable driving. One participant commented that their driving speed in VR was similar to the real world: "*I felt I was driving much slower with poor conditions. I think my speed was reflective of how I would actually drive in the given conditions.*" However, some participants reported other reasons for their speed choice. For example, several participants indicated being aware that the driving scenario was artificial and driving faster than they would in similar conditions in the real world. Other comments were related to task completion or compliance, perceived risk, and accident prevention. Many participants also commented that they tried to remain close to the lead vehicle. For example: "*My goal was mainly to follow the car in front of me, so I was trying to keep their speed. However, when the car would disappear, I think my speed went up because I was*

Table 3 Mixed-effects model analysis of distance headway (significant *p* values in bold)

Variable	Condition	Coefficient	Standard error	*p* value	Confidence interval	
Intercept		27.97	2.213	0.000	23.632	32.307
Light	Night	0.88	1.156	0.447	−1.385	3.144
Atmosphere	Fog	0.82	2.922	0.779	−4.907	6.548
Extinction	0.05 m^{-1}	−5.333	2.299	**0.020**	−9.838	−0.827
Extinction	0.10 m^{-1}	−5.141	1.711	**0.003**	−8.494	−1.788
Extinction	0.20 m^{-1}	−3.575	1.544	**0.021**	−6.601	−0.548
Extinction	0.40 m^{-1}	−4.386	1.971	**0.026**	−8.249	−0.523
Participant Variability		71.667	2.996			

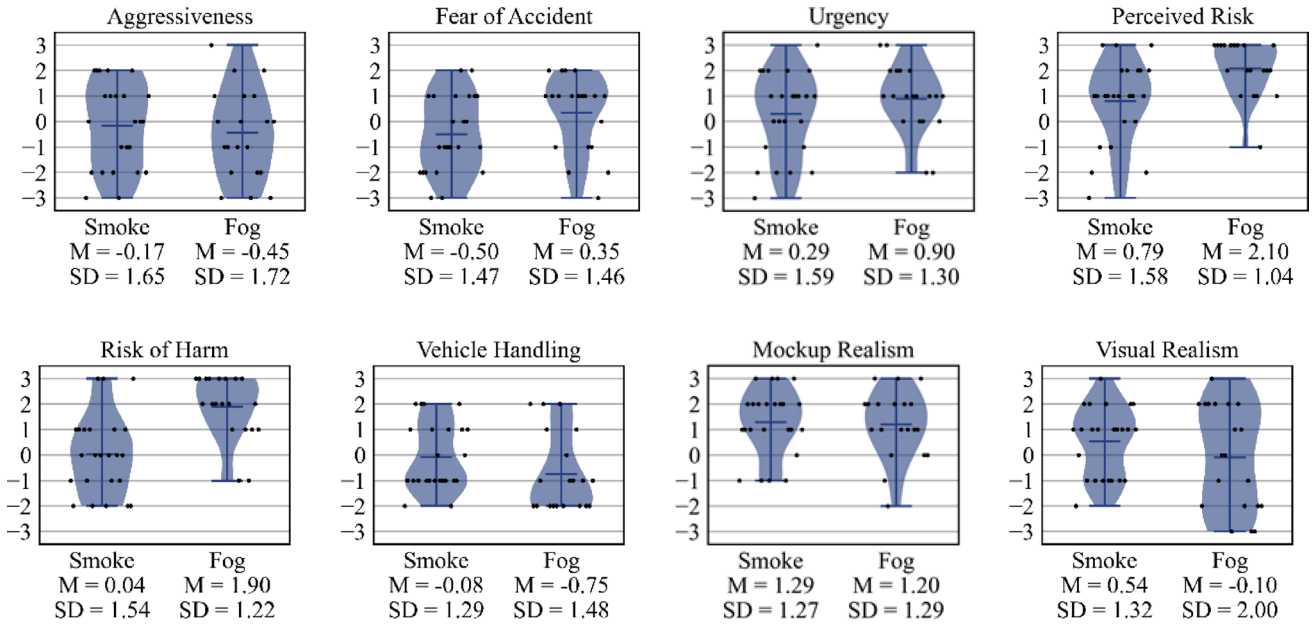

Fig. 8 Individual and mean ratings from the driving scenario questionnaire by condition (n=44). The markers represent individual data points; the line inside the violins represents the mean

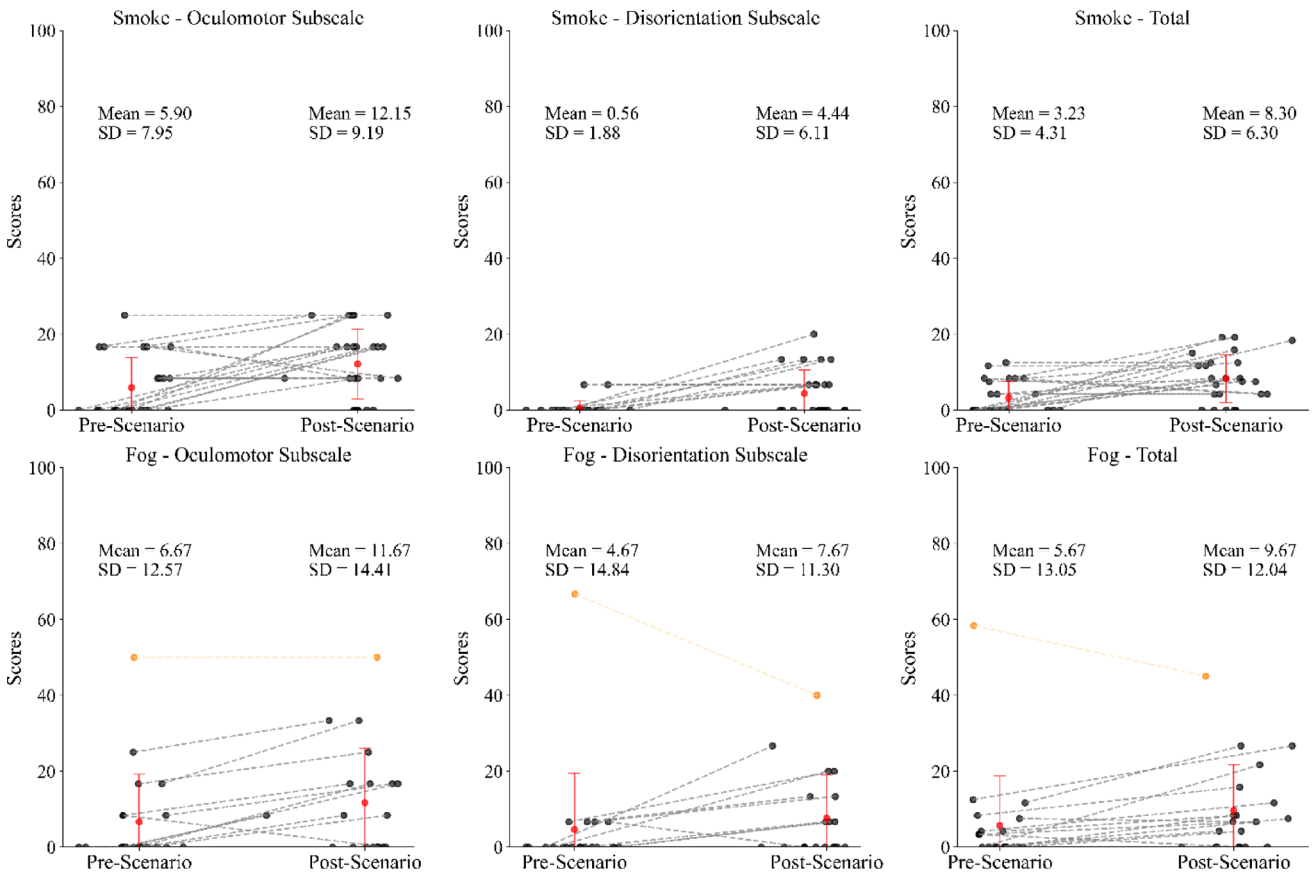

Fig. 9 Individual and mean scores from the Virtual Reality Sickness Questionnaire by condition (n=44). The black markers represent individual data points; the orange markers represent an outlier; the red markers represent the mean. The plots only include complete datasets

Table 4 Mean subscale and total scores on the VRSQ (cybersickness measure), with and without an outlier

Questionnaire	With outlier		Without outlier	
	n	Mean	n	Mean
VRSQ – Pre				
Oculomotor	51	6.21	50	5.33
Disorientation		2.22		0.93
Total		4.22		3.13
VRSQ – Post				
Oculomotor	44	11.93	43	11.05
Disorientation		5.91		5.12
Total		8.92		8.08

Means are rounded up to two decimal places

trying to get back to it. I would then follow the lines instead of the car."

Participants seemed to experience higher overall satisfaction when the VR experience was in line with their expectations. While participants reported finding some components of driving in VR similar to the real world, many noticed differences between the driving simulator and real-world vehicles. For example, one participant found the driving simulator's deceleration abrupt, which contributed to cybersickness: "*It was pretty good. My only feedback is that when you released the accelerator the sim car felt like it was slowing down quite abruptly and this made me feel nauseous. The sim in general was good. That's about how I would feel in a forest with fog. In real life I would be able to pace the car better.*"

Positive feedback included finding the VR driving scenario realistic, fun/enjoyable, safe, easy to use, and immersive. Participants appreciated the simplicity of the driving task, the physical driving simulator/mock-up, and the rendering of the smoke/fog (e.g., felt like they were actually driving in smoke/fog) and of day/night. Negative feedback included finding the VR driving scenario unrealistic/artificial and suggesting improvements to visual graphics, audio, and car/floor pedal responsiveness. Participants suggested increasing scenario complexity by including additional components, such as obstacles, burning trees, and traffic. For example, one participant suggested adding "*Bur[n]ing trees either in the distance or on the side of the road. A lot more vehicles lined up trying to get out. Emergency vehicles along the road lights flashing. I think this is the reality for many people experiencing an emergency evacuation.*"

5 Discussion

The following hypotheses were put forward: (1) participants will maintain a larger headway during nighttime than during daytime and (2) participants will maintain a larger headway in conditions with a high density of smoke or fog than in conditions with a low density of smoke or fog. The results suggest that hypothesis 1 was not supported, as lighting condition did not have a significant effect on headway. Hypothesis 2 was partially supported. Specifically, the results showed that the extinction coefficient seemed to have an effect on headway, but no consistent trend in mean headway across extinction coefficients was observed.

The results from the headway data revealed that the extinction coefficient (levels of smoke/fog) significantly influenced distance headway. In contrast, lighting condition (day/night) and atmospheric condition (smoke/fog) did not significantly affect distance headway. The results suggested that the mean distance headway was similar across extinction coefficients. A possible explanation could be that the participants kept a large distance because their risk perception increased with decreasing visibility. In the feedback survey, many participants reported that they were afraid of colliding with the lead vehicle or of driving off the pavement, which is consistent with this explanation. However, other participants indicated that they were aware that this was a simulation and that no accident in the physical environment would occur, which suggests that there were individual differences in risk perception.

Following behavior varied with the visibility in the trials. Specifically, 90% of participants followed in the trials without smoke or fog, but only 26% of participants followed when smoke or fog was thin. The percentage of following participants increased in trials with thicker smoke or fog. Participants might have felt more comfortable driving alone in thin smoke, while they preferred to stay close to the lead vehicle and use it as a reference to know where the road was located in thicker smoke. The results from the headway data also revealed an interesting behavioral pattern in following distance, showing individual variability within each visibility condition. Specifically, some participants kept a minimal headway regardless of visibility. The results from the feedback survey suggested that overall, some participants kept a smaller headway to try to maintain visual contact with the lead vehicle whereas others kept a larger headway in trials with higher smoke or fog. Broughton et al. (2007) observed a similar effect where participants either stayed within the visible range of the lead vehicle ("non-laggers") or lagged beyond the visible range of the lead vehicle ("laggers") when driving through simulated fog conditions in a driving simulator. The results from the current study also seem to support Saffarian et al. (2012) who suggested that the lead vehicle might act as a guide. Similarly, Rohaert et al. (2025b) found that participants maintained a shorter distance with the vehicle in front of them (distance headway) in conditions with denser smoke. The authors suggested that participants may have used the lead vehicle as a guide to position themselves on the road. In addition, participants' feedback was comparable to the current study: several participants

reported driving closer to the lead vehicle whereas others increased their following distance to prioritize safety. Note that Rohaert et al. (2025b) and the current study used different study designs (e.g., leading vehicle driving at a variable speed versus a constant speed, additional vehicles on the road versus participant is alone on the road).

In addition, the results from the headway data showed that participants were more likely to follow during the last five trials that they completed. This indicates that the participants might not have followed the lead vehicle in the beginning as they struggled with handling the driving simulator. Another reason might be that they decided to drive more carefully at the start as they had not yet learned the course of the trial (specifically, the repeated road geometry and the speed profile of the lead vehicle). Due to the randomized trial order for each participant, this learning effect does not lead to biases when looking at the effect of light, atmosphere, or extinction coefficient. This observation aligns with findings from Intini et al. (2019), which suggested that increased route familiarity can lead to faster driving and more confident behavior.

Interestingly, the following percentage appeared to be 10% higher for the fog condition than for the smoke condition. The results from the driving scenario questionnaire showed that mean participant ratings for perceived risk and risk of harm were higher for the fog condition than for the smoke condition. This might be due to the wording of task instructions being slightly different for each condition. Specifically, participants in the smoke condition were told that the local public authority had ordered a mandatory wildfire evacuation, whereas those in the fog condition were told that the local public authority had issued a fog warning. These instructions might have contributed to varying levels of perceived risk and risk of harm in participants depending on their assigned atmospheric condition. In addition, only four out of 51 participants had previous experience with a wildfire whereas most participants likely had previous experience with fog.

The results from the usability items suggested that overall, participants found the driving simulator easy to use and comfortable and that it had the functionalities that they expected it to have (see Appendix 3 for the full results). Participants suggested making improvements to the driving scenario to increase realism. Specific suggestions focused on improving or including additional visual components (burning trees, obstacles, traffic), audio components (wind, warnings on the radio, more realistic engine sound), and haptic components (vibrations). Future studies could include additional features (e.g., ember showers, wind) in the virtual environment to enhance scenario realism.

The research team initially hypothesized that participants will drive faster (1) during daytime than during nighttime and (2) in conditions with a low density of smoke or fog than in conditions with a high density of smoke or fog (see Ronchi et al. 2024). Since the lead vehicle capped participants' driving speed during the trials, these hypotheses could not be tested given the current study design. Future studies should consider a study design that allows participants to drive at their preferred speed, enabling a more accurate measurement of their natural driving behavior in reduced visibility conditions (e.g., Rohaert et al. 2025b).

Another limitation of the study was the responsiveness of the floor pedals. Participants reported that the virtual car accelerated too slowly when pressing on the gas pedal and decelerated too quickly when releasing it. This could have an impact on driving speed and headway as it was more difficult to control the car's speed. The pedal responsiveness will be fine-tuned in future work.

The research team balanced maximizing data collection and minimizing cybersickness among participants. For example, participants completed the smoke or the fog scenario. While completing both scenarios would have increased statistical power, it would also have increased the risk of cybersickness. Minimizing user discomfort and cybersickness is important for a positive VR experience. Further improvements should be made to the pedal responsiveness and vehicle physics. Participants withdrawing from the study due to cybersickness also suggests that VR may not be universally suitable for all individuals. Future research could use alternative exposure durations or motion design to reduce dropout.

Driving in a VR simulator differs from driving in the real world. For example, in the current study, participants were aware that the driving scenario was artificial and that they were physically safe in a laboratory, which could have led them to drive faster in poor visibility than they would if they encountered a similar situation in the real world. In addition, previous studies have shown that users can overestimate (Choudhary et al. 2021; Peillard et al. 2019) or underestimate distances in VR (Buck et al. 2021; Creem-Regehr et al. 2005; Renner et al. 2013). It is possible that participants drove closer or further away from the lead vehicle than they would in the real world as it was more difficult to estimate the distance between the cars. However, previous research has shown that VR is a valid tool for examining headways (Risto & Martens 2014; Rohaert et al. 2025b). Future work could compare driving in VR versus in the real world in low/high visibility conditions (e.g., headway during day versus night).

Despite VR's limitations, the setup in use was determined to be an acceptable tool for examining driving behavior in wildfires since the aim was to assess relative (not absolute) differences between experimental conditions that would be dangerous to study in the real world. Conducting a driving

Table 5 Overview of rendering settings and image sources (photographs) and associated example renderings

		Day	Night
Zero density (no fog, no smoke)	Directional light intensity	8	0.25
	Zero density (no smoke, no fog)	Day skybox Sun color 255, 214, 190 Ambient light 191, 191, 191 Equator ambient 153, 133, 130 Ground 51, 45, 43 Fog density 0.003 Fog color 0, 0, 0	Night skybox Sun color 181, 205, 255 Ambient light 10, 10, 10 Equator ambient 59, 59, 59 Ground 105, 89, 89 Fog density 0.003 Fog color 0, 0, 0
Fog	Directional light intensity	8	1
	Color (*)	200, 200, 220	45, 55, 65
Smoke	Directional light intensity	8	1
	Color (*)	240, 180, 110	90, 30, 5

(*) Color: Tint color of single-color skybox, tint fog color, color environmental light (single color), and directional light color. RGB values were determined through non-calibrated visual inspection

study in VR has practical, ethical, and financial benefits over conducting a similar study in the real world. For instance, studying headway in poor visibility conditions in the real world would require additional resources (a large outdoor space, vehicles, an experienced lead driver, etc.). Furthermore, VR provides detailed information on the visibility conditions at the driver level, which are more difficult to obtain in real-world scenarios. VR also allows experimental control and repeatability of conditions, which can be challenging in the real world as it is not possible to directly manipulate certain variables, such as weather conditions.

6 Conclusion

Few previous studies have examined driving behavior in reduced visibility conditions, particularly when other vehicles are present on the road. The present study found supporting evidence that visibility influences how drivers keep distance from cars ahead of them. However, no evidence was found that this relationship was influenced by the scenario (day/night and smoke/fog). Given the limitations of the methodology (VR) and the observation that not all participants followed the car, future research is needed to fully understand how changes in visibility due to wildfires could affect driving behavior. The understanding of the relationship between headway and reduced visibility helps to provide more accurate estimations of wildfire evacuation times, which can subsequently inform emergency response.

Appendix 1: Rendering settings in Unity for the pilot and main VR studies

This appendix presents an overview of the rendering settings used in the virtual environment (Table 5) for both the pilot VR study and the main VR driving study.

The VR trials were developed using Unity version 2020.3.141f. The color of the smoke and fog were determined by visually inspecting photos of real-world wildfire smoke and fog and reproducing the colors as closely as possible in Unity. Screenshots of the associated conditions in the virtual environment are shown in Fig. 2 within the main text (note that the pilot study did not include any cars other than the one driven by the participant).

The smoke and fog were implemented through a script using Unity's fog settings:

- Fog color: set the color of the smoke and fog using RGB values. For each condition, the RGB values were based on image internet searches.
- Fog mode: set the fog mode to "Exponential".
- Fog density: set the fog density values (e.g., 0.20). This value corresponds to the extinction coefficient of the smoke or fog.

Implementing realistic fog or smoke physics in real-time visualizations in Unity is challenging due to the computational costs involved in simulating complex light interactions, such as multiple scattering and volumetric effects (Wahlqvist & Rubini 2023). Achieving accurate visuals for scattering, absorption, and emission of light within a dynamic, three-dimensional fog or smoke environment demands sophisticated calculations that may exceed the real-time processing capabilities of current hardware. Therefore, the fog and smoke were rendered using the built-in fog function, which is applied post-process.

The built-in fog function processes rapidly and therefore are commonly used in video games to add the perception of depth and improve performance by avoiding rendering objects at far distances. It is also commonly used by researchers (Davis et al. 2023; Wetterberg et al. 2021). Nevertheless, some limitations of the post-process function should be mentioned:

- The fog/smoke is distributed uniformly over the entire field of view. Real fog and smoke might vary in thickness over space.
- The fog/smoke is static. Aerodynamic effects by wind and obstacles are not included.
- There are no interactions with light. The "true color" of the object behind the fog is calculated assuming the

same directional light from the sun and environmental light. Light is not absorbed and scattered as it would be by real fog and smoke.

Appendix 2: Full list of measures from the main VR driving study

Below is a list of measures that participants completed throughout the main driving study:

Background questionnaire

The background questionnaire inquired about participants' age, gender, driver's license, driving experience, VR and gaming experience, previous experience with evacuating from a wildfire, etc. Participants completed the demographic questionnaire prior to the VR immersion.

Driving behavior

During the VR immersion, participants' driving behavior (timestamps, position and rotation, speed, headway) was automatically recorded via output files generated by Unity.

Driving scenario

This questionnaire inquired about the driving scenario using a Likert-type scale from -3 to 3 (e.g., "How afraid were you of getting in an accident during the simulation?"). The questionnaire also contained an open-ended question: "How much was your speed choice affected by the wildfire smoke (or fog) and by knowing you were performing an evacuation (or by knowing that a fog warning was issued)?" The questions were based on Wetterberg et al. (2021).

Usability

This questionnaire contained items about the driving simulator's usability (e.g., "I thought the VR driving simulator was easy to use"), which were rated on a Likert scale from 1 (*strongly disagree*) to 5 (*strongly agree*). The items were based on the System Usability Scale (Brooke et al., 1996).

Presence

A single item on presence assessed the extent to which participants felt like they were actually "there" in the virtual environment: "On a scale from 0 (*not at all*) to 10 (*totally*), to which extent do you feel present in the virtual environment, as if you were really there?" The question was based on Bouchard et al. (2008).

Cybersickness

The Virtual Reality Sickness Questionnaire (VRSQ) (a short version of the Simulator Sickness Questionnaire [SSQ], Kim et al. 2018) was used to assess cybersickness. It is rated on a scale of 0 (*none*) to 3 (*severe*).

Feedback survey

A short questionnaire contained five open-ended questions to obtain qualitative feedback about participants' experience (e.g., "Are there any specific components about the VR driving simulation that you liked and/or did not like? Please explain why you liked or did not like them.").

Appendix 3: Secondary results of the main VR driving study

This appendix presents results that do not directly address the objective or the hypotheses of the main driving study. For example, a secondary objective of the main driving study was to assess the usability of the driving simulator following improvements to the virtual environment, specifically to its interface and frame rate.

Participants filled out online questionnaires before and after the VR experiment. Note that one outlier for the VRSQ (cybersickness measure) was identified by visually inspecting the data; the outlier is included in the descriptive statistics for the VRSQ in Table 6. Demographic data can be found in Table 7.

Nine participants withdrew from the study due to cybersickness (17.65% of the sample). Eight out of nine (88.89%) of the participants who withdrew were women. All participants who withdrew were above the age of 30 (M = 48.67, SD = 9.51) and had little or no previous experience using VR. The mean age of participants who completed the study was 38.78 (SD = 8.83).

Independent samples t-tests (see Table 8) showed that the mean ratings on the self-report questionnaires did not significantly differ between the smoke and fog conditions, except for two items on the driving scenario questionnaire. Specifically, independent samples t-tests indicated that the difference in mean ratings for the items "Perceived risk" and "Risk of harm" between the two conditions was significant: $t_{(42)} = -3.10$, $p = 0.003$ and $t_{(42)} = -4.27$, $p = 0.0001$, respectively. Note that the results above were significant even after applying the Holm-Bonferroni correction: $\alpha/(\text{N-rank}+1)$, or $0.05/(8\text{-rank}+1)$ as eight independent samples t-tests were performed for the Driving Scenario questionnaire.

Table 6 Descriptive statistics from self-report questionnaires (pre: $n=51$; post: $n=44$)

Questionnaire	Mean	SD	Min	Max
Driving Scenario – Post				
Aggressiveness	-0.30	1.71	-3	3
Fear of accident	-0.11	1.54	-3	2
Urgency	0.57	1.52	-3	3
Perceived risk	1.39	1.53	-3	3
Risk of harm	0.89	1.70	-2	3
Vehicle handling	-0.39	1.43	-2	2
Mockup realism	1.25	1.30	-2	3
Visual realism	0.25	1.71	-3	3
Usability – Post				
Ease of use	4.52	0.85	1	5
Comfort	4.16	1.06	1	5
Functionalities	4.02	1.09	1	5
Presence – Post	6.48	1.80	2	10
VRSQ – Pre				
Oculomotor	6.21	10.3	0	50
Disorientation	2.22	9.49	0	66.6
Total	4.22	8.90	0	58.33
VRSQ – Post				
Oculomotor	11.9	11.7	0	50
Disorientation	5.91	8.89	0	40
Total	8.92	9.26	0	45

Means, standard deviations (SD), minimum values (Min), and maximum values (Max) are rounded up to two decimal places

Table 8 Results from independent samples t-tests between smoke and fog conditions ($n=44$, except VRSQ: $n=43$)

Questionnaire	*df*	*t*	*p*	*d*
VRSQ – Pre				
Oculomotor	41	0.20	0.841	0.06
Disorientation	41	-1.46	0.152	-0.41
Total	41	-0.19	0.854	-0.05
VRSQ – Post				
Oculomotor	41	0.79	0.433	0.24
Disorientation	41	-0.68	0.501	-0.21
Total	41	0.21	0.834	0.06
Driving Scenario – Post				
Aggressiveness	42	0.54	0.589	0.16
Fear of accident	42	-1.87	0.068	-0.57
Urgency	42	-1.34	0.188	-0.41
Perceived risk	42	-3.10	0.003**	-0.94
Risk of harm	42	-4.27	0.0001***	-1.29
Vehicle handling	42	1.56	0.126	0.47
Mockup realism	42	0.23	0.818	0.07
Visual realism	42	1.25	0.220	0.38
Usability – Post				
Ease of use	42	-1.27	0.210	-0.39
Comfort	42	-0.81	0.425	-0.24
Functionalities	42	0.40	0.691	0.12
Presence – Post	42	-0.41	0.684	-0.12

** $=p\leq 0.01$; *** $=p\leq 0.001$

Statistics are rounded up to two decimal places; p *values are rounded up to three decimal places*

Table 7 Frequency of responses from the background questionnaire ($n=51$)

Item	Responses	Frequency	Percentage
Gender	Woman	26	50.98%
	Man	25	49.02%
License ownership	Between 7 and 8 years	1	1.96%
	Between 8 and 9 years	1	1.96%
	Between 9 and 10 years	2	3.92%
	More than 10 years	47	92.16%
Driving experience (frequency)	Daily	42	82.35%
	Weekly	8	15.69%
	Seasonal	1	1.96%
Driving experience (distance)	<50 km/week	8	15.69%
	50–100 km/week	13	25.49%
	100–150 km/week	8	15.69%
	150–200 km/week	6	11.76%
	200–250 km/week	5	9.80%
	250–300 km/week	4	7.84%
	>300 km/week	7	13.73%
Country where most driving experience gained	In Canada	50	98.04%
	Outside Canada	1	1.96%
Car ownership	Own a car	48	94.12%
	Do not own a car	3	5.88%
Experience with transmission	Automatic transmission	29	56.86%
	Equally familiar with both types	18	35.29%
	Manual transmission	4	7.84%
Experience with VR	Never used it	24	47.06%
	Tried using it a few times	24	47.06%
	Used to use but not anymore	2	3.92%
	Use less than every month	1	1.96%
Experience with video gaming	Never played	6	11.76%
	Tried playing a few times	7	13.73%
	Used to play but not anymore	17	33.33%
	Play less than every month	5	9.80%
	Play every month	5	9.80%
	Play every week	8	15.69%
	Play daily	3	5.88%
Experience with wildfire evacuation	No	47	92.16%
	Yes	4	7.84%

Percentages are rounded up to two decimal places; some percentages might not add up exactly to 100%

Cybersickness

Independent samples t-tests (see Table 8) showed that the difference in mean cybersickness scores (Oculomotor, Disorientation, and Total scores) between the smoke and the fog conditions was not significant before or after the VR experiment. Note that the outlier was not included in the independent t-tests.

Table 9 Results from paired samples t-tests between VRSQ scores before and after the VR experiment (smoke: $n=44$; fog: $n=43$)

Condition	Questionnaire	*df*	*t*	*p*	*d*
	VRSQ – Pre-Post				
Smoke	Oculomotor	23	-3.19	0.004**	-0.65
	Disorientation	23	-3.08	0.005**	-0.63
	Total	23	-3.55	0.002**	-0.72
	VRSQ – Pre-Post				
Fog	Oculomotor	18	-3.31	0.004**	-0.76
	Disorientation	18	-2.48	0.023*	-0.57
	Total	18	-3.32	0.004**	-0.76

*=$p \leq 0.05$; **=$p \leq 0.01$

Statistics are rounded up to two decimal places; p *values are rounded up to three decimal places*

These results should be interpreted with caution as a few participants who withdrew from the study due to cybersickness ($n=7$) did not complete the questionnaires after the VR experiment. Many of the participants who withdrew reported experiencing motion sickness or nausea. As such, the mean VRSQ scores might be higher than those reported here.

See Fig. 9 for individual and mean scores from the VRSQ by condition. Note that the line plots in the figure only include complete datasets (i.e., participants filled out the VRSQ before and after the VR experiment).

Paired samples t-tests (see Table 9) showed that the difference between mean cybersickness scores before and after the VR experiment (Oculomotor, Disorientation, and Total scores) was significant for both the smoke condition and the fog condition. The results were significant even after applying the Holm-Bonferroni correction: α/(N-rank+1), or 0.05/(6-rank+1) as six paired samples t-tests were performed. Note that the outlier, identified by visually inspecting the data (see the orange markers in Fig. 9), was not included in the paired-samples t-tests.

Usability

Participants' ratings from the Usability Questionnaire ranged from 1 (*Strongly disagree*) to 5 (*Strongly agree*). A descriptive analysis indicated that mean participant ratings were positive. The item "Ease of use" had the highest mean rating (M=4.52, SD=0.85). The item "Functionalities" had the lowest mean rating (M=4.02, SD=1.09). Independent

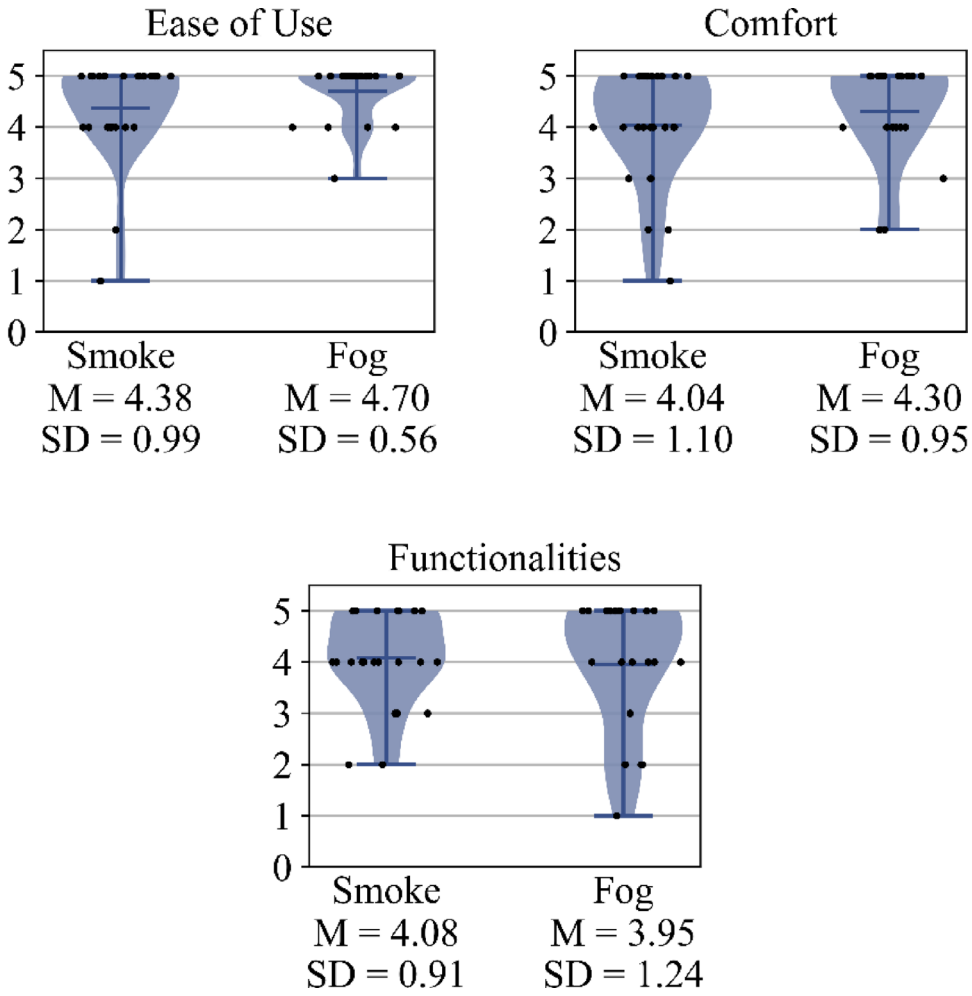

Fig. 10 Individual and mean ratings from the usability questionnaire by condition (n=44). The markers represent individual data points; the line inside the violins represents the mean

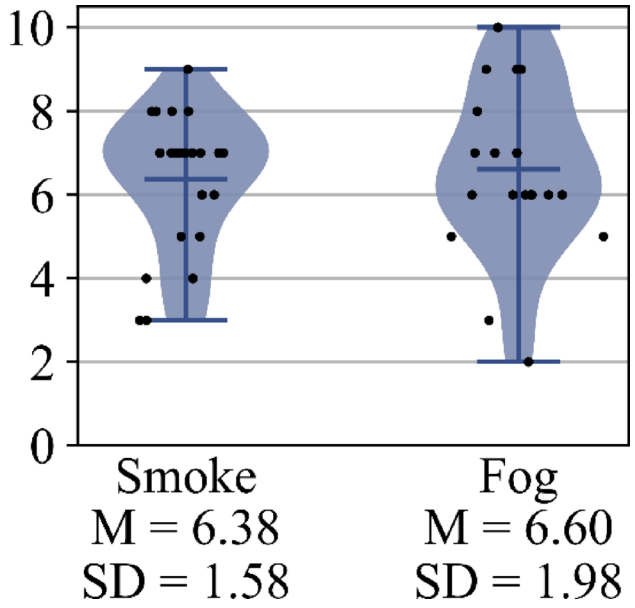

Fig. 11 Individual and mean ratings from the presence item by condition (n = 44). The markers represent individual data points; the line inside the violins represents the mean

samples t-tests (see Table 7) showed that the difference in mean usability ratings for each item ("Ease of use", "Comfort", and "Functionalities") between the smoke and fog conditions was not significant. See Fig. 10 for individual and mean ratings from the Usability Questionnaire by condition.

Presence

Participants' ratings from the single-item presence measure ranged from 2 to 10 (0 being the lowest possible score and 10 the highest for this measure). A descriptive analysis showed that mean participant ratings were positive. An independent samples t-test (see Table 7) showed that the difference in mean presence ratings between the smoke and the fog conditions was not significant. See Fig. 11 for individual and mean ratings from the single-item presence measure.

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Data Availability Deidentified data that support the findings of this study can be found in the following repository: https://nrc-digital-repository.canada.ca/eng/search/?q=*&fc=%2Bcn%3Adatasets&s=rcd&pg=1

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval The pilot VR study on visibility and the main VR driving study were approved by the National Research Council of Canada's Research Ethics Board (protocol #2023–63). All experimental procedures performed involving human participants were in accordance with the institutional research committee ethical guidelines. All participants gave their written informed consent prior to participating.

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