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The effect of contrast on pedestrians' perception of vehicle speed in different road environments

Jennifer Sudkamp, David Souto

School of Psychology and Vision Sciences, University of Leicester, UK

<u>Corresponding author:</u>

Jennifer Sudkamp

College of Life Sciences

University of Leicester

University Road, Leicester, LE1 7RH, UK

+44 (0)116 229 7184

Email address: js993@leicester.ac.uk

Abstract

It is well known in the psychophysical literature that low visual contrasts can lead observers to misestimate the speed of moving objects. This effect can have important consequences for traffic safety when navigating under low visibility due to adverse weather conditions (e.g., fog) or visual impairments. So far, road traffic research has primarily focused on the perception of self-motion during driving showing that drivers can both under- and overestimate their own driving speed depending on the spatial distribution of contrast. In two experiments, we used a two-interval forced choice discrimination task to investigate whether pedestrians would be subject to similar biases when estimating the speed of approaching vehicles in a simulated traffic scene. We found that the perceived vehicle speed decreased when the contrast of the view was reduced uniformly but increased when contrast was reduced in a distance-dependent manner, simulating more realistically visibility in fog. The increase of the perceived vehicle speed in simulated fog occurred in bare and visually more complex road environments including either roadside trees or road markings. The origins of such misperceptions, specifically in fog, remain unclear. The temporal integration of motion signals in combination with a lack in speed constancy, and the illusion of acceleration due to the dynamic contrast-change of the vehicle constitute potential explanations that need further investigation.

Keywords: Visibility, Contrast, Fog, Speed Perception, Pedestrian Safety

1 Introduction

The visual contrast of an object, i.e., the extent to which it stands out against the background, affects not only the ability to detect the object, but it can also lead observers to misestimate its speed. Psychophysical studies show that a reduction in contrast often leads to a reduction in the perceived speed of moving stimuli. At slow speeds, the perceived speed of a drifting sinusoidal grating decreases when its contrast is reduced (Thompson, 1982; Stone & Thompson, 1992; Champion & Warren, 2017). Similar effects occur across a wide range of simple stimuli including linear and radial random dot motion, translating discs, and expanding and contracting patterns simulating motion-in-depth (Blakemore & Snowden, 1999; Moscatelli, Caleia, Zago & Laquaniti, 2019; Brooks, 2001).

In natural environments, visibility may be compromised by a reduction in contrast, for example, due to adverse weather conditions (e.g., fog) or individual visual impairments affecting retinal image contrast (e.g., cataracts). This can have important consequences in road traffic when a road user's decision-making is based on biased motion estimates. In driving, the effects of visibility have been well studied. Observers perceive their driving speed to be slower, are poorer at discriminating speeds and drive faster when accelerating to a set target speed (without the help of a speedometer) when the global contrast of their view is reduced (Horswill & Plooy, 2008; Pretto, Bresciani, Rainer & Bülthoff, 2012; Snowden, Stimpson & Ruddle, 1998). Much less is known about the effects of contrast on pedestrians, although there are indications that contrast may as well affect other navigational tasks, such as road-crossing decisions. Pedestrians' gap acceptance when crossing a road often correlates with the time-to-arrival of approaching vehicles at the crossing point (Petzold, 2014; Terwilliger et al., 2019). Although observers are able to judge the time-to-arrival of an approaching object by optical variables, such as the ratio between its retinal image size and rate of expansion (e.g., Lee, 1976; Lee, Young, Reddish, Lough, & Clayton, 1983), perceptual biases affecting its perceived speed and distance are often found to also affect time-to-arrival estimates. For example, a reduction in contrast lengthens the perceived time-to-arrival both when an object is viewed moving across the frontoparallel plane (Battaglini, Campana & Casco, 2013) and when viewed frontally as if approaching the observer (Hecht, Brendel, Wessels & Bernhard, 2021). The increase of the perceived time-to-arrival supposedly results from a reduction in the perceived speed or, alternatively in the latter case, an increase of the perceived distance. Consistent with these results, pedestrians have been found to accept smaller safety gaps in front of vehicles painted with lighter compared to darker colors (Feldstein & Peli, 2020). As lighter vehicles presented a lower contrast against the well-lit background, this behavior has been attributed to contrast-induced changes in the perceived vehicle kinematics.

Another aspect that has so far received little attention concerns the specific effect of naturally occurring fog on road user perception. Pretto et al. (2012) pointed out that a global reduction of contrast, i.e., a uniform reduction disregarding object location, does not reflect well the visibility experienced in natural fog. Instead of reducing contrast uniformly, fog affects contrast in a distance-dependent manner, whereby objects close to the observer have a higher contrast than objects farther away from the observer. A simulation of fog, in which contrast decreased exponentially with the distance to the observer, resulted in the opposite effect to what has been observed with a global reduction of contrast: Drivers overestimated their own speed and accordingly produced lower driving speeds (Pretto et al., 2012). To account for the effect, the authors suggest that fog reduces the availability of optic flow information from the driver's central central visual field (Pretto et al., 2012; Pretto & Chatziastros, 2006). For a driver looking at the road ahead towards the horizon, the optic flow information in the peripheral part of the visual field would mainly derive from areas that are close to the vehicle and therefore relatively unaffected by a fog-induced contrast reduction. Instead fog primarily masks the central part of the driver's visual field corresponding to the road ahead at greater distance. The overestimation of speed in fog is thus proposed to result from a bias in the proximal stimulus from which the driving speed is derived, as the faster part of the optic flow in the periphery is relatively more visible than the central, slower part of the optic flow. Given this explanation, it remains unclear whether the effect of fog would translate to estimates of object motion, such as to a pedestrian assessing the speed of an approaching vehicle, as there is no global optic flow information to parse in this case. Instead, when viewed from a pedestrian's point of view (from the edge of a straight road), vehicle motion in retinal coordinates amounts to linear translation of the vehicle across the frontoparallel plane as well as its expansion. While a reduction in the perceived speed following a uniform contrast reduction has been documented both for linear translation as well as for the expansion of simple stimuli (Blakemore & Snowden, 1999), the effects of distance-dependent changes of contrast on these types of motion cues remain unclear.

To explore whether pedestrians' speed judgements are similarly affected by visual contrast as was shown for drivers estimating their own driving speed, the present study investigated the effects of contrast on perceived vehicle speed in a virtual road-crossing scenario. In a first experiment, which was conducted online and used a remote testing paradigm, we aimed at testing whether different contrast distributions would result in different perceptual speed biases similar to what has been shown for drivers estimating their own driving speeds. Vehicles were shown approaching the observer as if standing at the edge of a road under different visibility conditions, including a uniform reduction of contrast across the virtual scene and two distance-dependent contrast reductions simulating visibility in either low- or high-density fog. In a two-interval forced-choice task, one vehicle was always shown at full contrast, while the other was subject to one of the contrast manipulations. To determine the point of subjective equality (PSE) as a measure for the perceived vehicle speed, observers were asked to select the vehicle that they believed was driving faster. In a second experiment, we investigated the effect of fog in different road environments and under more controlled viewing conditions. The second experiment employed the same two-interval forced choice task to compare perceived vehicle speed under clear view and low-density fog conditions while either road marking or roadside trees were added to the scene. As the contrast of the depicted road scenes may have differed between participants in the remote version of the experiment (depending on the individual hardware setup and viewing conditions under which participants completed the experiment), the second experiment was conducted in a computer room using the same display and hardware setup for all participants.

Based on the previously reported effects of contrast on speed perception for simple stimuli and in driving, we predicted that the perceived vehicle speed would decrease when the overall contrast of our traffic scene was reduced uniformly. Supposing that pedestrians' speed judgements are as well sensitive to the spatial distribution of contrast, we further predicted that the perceived speed would increase when the contrast of our scene was reduced in a distance-dependent manner, i.e., under simulated fog conditions. As contrast-induced biases are usually found to depend on the strength of the applied contrast manipulation, we further assumed that a fog-induced speed bias would depend on the simulated fog density so that the perceived speed would be higher in high- compared to low-density fog. Further, drawing on previous research showing that textured backgrounds can eliminate contrast-induced changes in the perceived speed and can improve the accuracy of speed judgements - by adding relative motion cues (e.g., Blakemore & Snowden, 2000) and by providing reference points to the distance of targets moving in depth (e.g., Rushton & Duke, 2009) - we assumed that a fog-induced bias would be more likely to occur in visually scarce compared to visually richer road environments including either road marking or roadside trees.

2 Methodology

2.1 Participants

For Experiment 1, 104 participants (62 female, 3 non-binary, 39 males) aged 18-50 years (M = 29.58 years, SD = 9.13 years) were recruited via Prolific (https://www.prolific.co; Palan & Schitter, 2018). Participants had to reside in the UK and had to have self-reported normal or corrected-to-normal vision to be eligible. Participants performed the experiment remotely via the Gorilla online experiment platform (https://gorilla.sc/; Anwyl-Irvine, Massonnié, Flitton, Kirkham & Evershed, 2020) and received monetary compensation (£8) for their participation. In Experiment 2, 56 students from the University of Leicester (47 female, 9 males) aged 18-33 years (M = 19.54 years, SD = 2.08 years) took part. All participants had self-reported normal or corrected-to-normal vision and received course credit for their participation. Participants in Experiment 2 performed the experiment as well via the Gorilla experiment platform but were supervised while they completed the study in a computer room in the University of Leicester, allowing us to use the same hardware and display for all participants.

Experiment 1 was preregistered (https://osf.io/dpcfq). The choice of sample size was based on a pilot study with a sample size of 40 participants. Experiment 2 was not preregistered but followed the preregistered criteria for data exclusion. The sample size of Experiment 2 was determined less formally by collecting as many participants as we could gather over four 1.5 hours testing sessions. As some authors suggest a data loss of up to 20-50% with online experiments (Finley & Penningroth, 2015), we reasoned that the second experiment sample could be considerably lower than in the remote version, as we controlled for screen size and testing conditions.

The study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the University of Leicester's ethics committee. Participants gave their informed consent prior to the experiments.

2.2 Apparatus

In Experiment 1, participants used their own hardware setup to perform the experiment remotely. We used the credit card task described in Li, Joo, Yeatman and Reinecke (2020) to estimate participants' monitor sizes. Estimated monitor sizes ranged from 11.3 to 46.3 inch (M = 17.9 inch, SD = 6.0 inch) and participants' self-reported viewing distances ranged from 22 to 130 cm (M = 56.8 cm, SD = 17.7 cm; three participants likely misunderstood the instructions and reported a viewing distance of 1 cm). Before the experiment started, participants were asked to adjust the brightness of their screen until they were able to see all 12 differing shades of grey of a band test image (bands ranging in equally sized encoded luminance steps from RGB = 0, 0, 0 to 255, 255, 255). All participants reported that they were able to see the differing shades before they started the experiment.

In Experiment 2, stimuli were displayed on HP 23.8-inch LCD monitors (1920 x 1080 pixels) at an approximate viewing distance of 60 cm.

2.3 Two-interval forced choice task

In each trial, participants compared the speed of two approaching vehicles. Stimuli were video sequences of a white vehicle approaching a zebra crossing from the right on a single-lane, rural road created in Unity3D 2018.3.1f1. Each sequence was displayed for 3 seconds and was preceded by a black fixation cross displayed for 0.5 seconds in the center of a uniform grey screen. In the standard interval of each trial, the vehicle was clearly visible and presented at full contrast while it approached the crossing area with a constant speed of 50 km/h. The comparison interval presented the vehicle under different visibility conditions (Experiment 1 & 2) and in different road environments (Experiment 2). The vehicle speed in the comparison interval varied across trials in seven steps (20, 30, 40, 50, 60, 70, 80 km/h). After they had seen both intervals, participants responded which of the two vehicles they perceived as being faster. To prevent participants from solely relying on the relative position of the two vehicles, the trajectory of the comparison vehicle varied such that both the standard and the comparison vehicle either started from the same position at the beginning of each interval (75 m from the stopping line) or ended at the same position by the end of each interval (33 m from the stopping line).

2.3 Experimental conditions

The standard interval of each trial displayed the original traffic scene at its full contrast (Figure 1A). Based on the standard scene, each objects' rendered surface color for the comparison interval was calculated as $C_{Original}$ * alpha + C_{Fog} * (1 – alpha), whereby C_{Fog} was set to a medium grey color (RGB = 128, 128, 128) and alpha varied depending on the respective visibility condition. In all traffic scenes, the horizon was uniformly grey (RGB = 128, 128, 128).

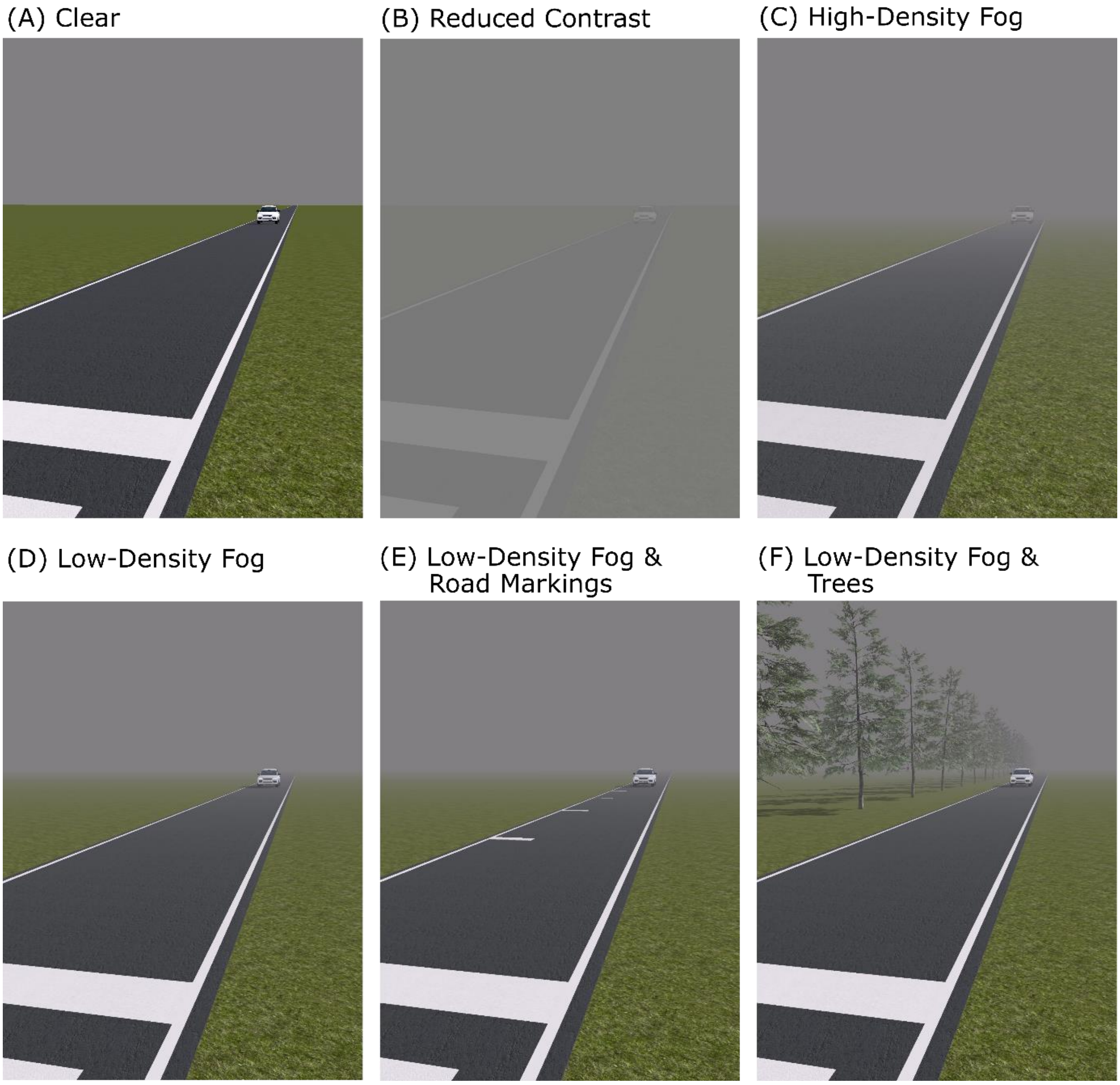

Figure 1. Example images of the virtual road environment. (A) The standard interval and clear view condition always depicted the road-crossing scene at full contrast. (B) Uniform contrast reduction condition with alpha = 0.01. (C) High-density fog condition with fog density = 0.05. (D) Low-density fog condition with fog density = 0.02. (E) Low-density fog and road markings. (F) Low-density fog and roadside trees. Sample videos of the conditions used in Experiment 1 and 2 are available online (https://doi.org/10.25392/leicester.data.1963539692/leicester.data.19635396).

Similar to the contrast manipulations reported in Pretto et al. (2012), Experiment 1 applied four visibility manipulations: The clear condition provided a clear view of the simulated traffic scene and did not apply a contrast manipulation, so that the visibility of the comparison vehicle was equal to that of the standard and remained constant across the trajectory (alpha = 1; Figure 1A). In the reduced contrast condition, the contrast of the comparison interval was reduced uniformly across the visual scene. As in the clear condition, the luminance and contrast of the vehicle relative to its surrounding remained constant across its trajectory (alpha = 0.1; Figure 1B). In the fog conditions, contrast was manipulated in a distance-dependent manner, so that objects closer to the observer appeared at a higher contrast than distant objects. To achieve this, we used the exponential fog effect in Unity, in which an object's rendered surface color depends on its simulated distance to the virtual camera as well as the density of the simulated fog (alpha = $e^{-\text{density} \cdot \text{distance}}$). In the high-density fog condition, the fog density was set to 0.05 (Figure 1C). In the low-density fog condition, the fog density was set to 0.02 (Figure 1D).

To test the effect of fog on the perceived vehicle speed in different road environments while keeping the overall completion time of the experiment feasible within one testing session, Experiment 2 employed only two contrast manipulations: The comparison vehicle was either displayed under clear view conditions or under simulated fog conditions with a fog-density of 0.02 corresponding to the clear view and low-density fog conditions of Experiment 1. The decision to choose low-density fog over high-density fog in the second experiment was based on the assumption that the low-density fog condition approximating visibility in moderate fog would practically be more relevant compared to the high-density fog condition approximating visibility in very thick to dense fog, which presumably constitutes a rather rare weather event. The vehicles were presented in three different environments by adding either road markings (Figure 1E), roadside trees (see Figure 1F) or no further cues to the original road traffic scene. Roadside trees were placed at a simulated distance of 3 meters away from the edge of the road and both road markings and trees were equally spaced 7 meters apart from each other.

The alpha distributions of all experimental conditions of Experiment 1 and 2 are shown in Figure 2. As the stimuli of Experiment 1 were presented remotely on participants' own monitor, we performed luminance measurements of the darkest and lightest point of the vehicle at the start and end position of the standard trajectory as well as of the surrounding asphalt and horizon on the monitor used in Experiment 2 for reference. The measured luminances and Michelson contrasts [(Lmax – Lmin)/(Lmax+Lmin)] are reported in Table 1. Sample videos of the conditions are available online (https://doi.org/10.25392/leicester.data.1963539692/leicester.data.19635396).

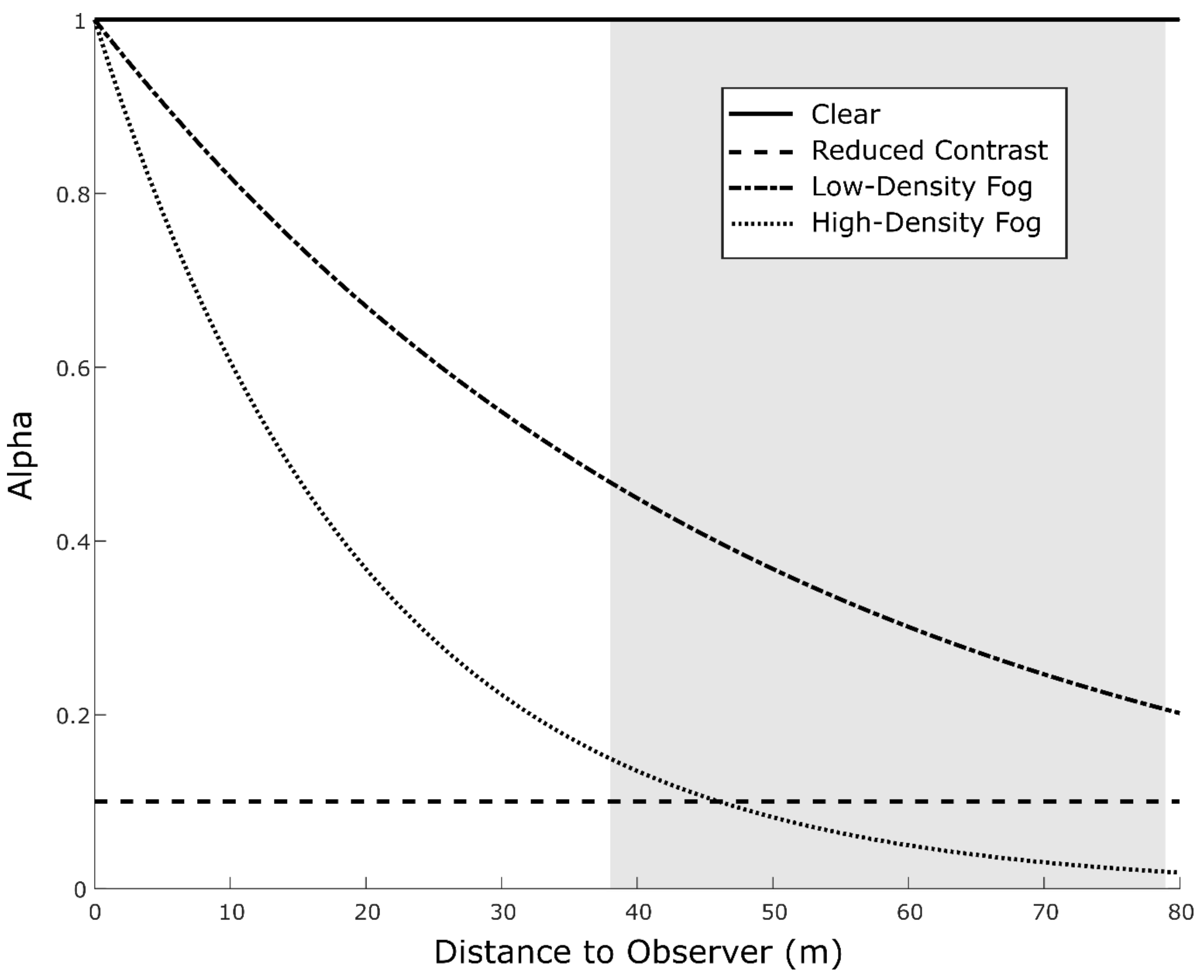

Figure 2. Alpha distribution across conditions. Each objects' rendered surface color in the simulated traffic scene was calculated as $C_{original}$ * alpha + C_{Fog} * (1 - alpha) with C_{Fog} = RGB(128, 128,128). In the clear view and reduced contrast conditions, alpha was constant. In the fog conditions, alpha depended on the simulated distance to the observer and the fog density (high fog density = 0.05, low fog density = 0.02; alpha = $e^{-\text{density} \cdot \text{distance}}$) . The grey background patch indicates the standard trajectory of a vehicle driving at 50 km/h during the 3 seconds display interval.

Table 1. *Luminance and contrast as measured on the reference monitor used in Experiment 2.*

	Luminance (cd/m²)					Michelson Contrast			
	Vehicle (L_{MIN}; L_{MAX})		Asphalt		Horizon	Vehicle/Asphalt		Vehicle/Horizon	
	at start position	at end position	at start position	at end position		at start position	at end position	at start position	at end position
Clear View	1; 238	1; 238	15	15	56	0.88	0.88	0.67	0.67
Reduced Contrast	47; 75	47; 75	49	49	56	0.21	0.21	0.15	0.15
Low-Density Fog	38; 106	17; 221	42	30	56	0.43	0.76	0.31	0.60
High-Density Fog	58; 64	49; 96	48	46	56	0.14	0.35	0.07	0.26

2.4 Experimental design

In Experiment 1, the combination of vehicle speeds (20, 30, 40, 50, 60, 70, 80 km/h), visibility conditions (clear, reduced contrast, low-density fog, high-density fog), interval orders (standard first, standard second), and trajectories (same start distance, same end distance) resulted in 112 unique trials.

In Experiment 2, the combination of vehicle speeds (20, 30, 40, 50, 60, 70, 80 km/h), visibility conditions (clear, low-density fog), road environments (no cues, trees, road markings), interval orders (standard first, standard second), and trajectories (same start distance, same end distance) resulted in 168 unique trials

In both experiments, participants performed three blocked repetitions of unique trials resulting in a total number of 336 trials for Experiment 1 and 504 trials for Experiment 2.

Vehicle speeds, visibility/environment conditions, interval orders and trajectories were randomized within each block.

2.4 Data preparation & analysis

For each participant and visibility condition of Experiment 1, we fitted a cumulative normal function to the proportion of trials in which the comparison vehicle was judged as being faster as a function of its speed (pooled over the two trajectories, interval orders and three repetitions, i.e., over 12 trials per vehicle speed level) using a maximum likelihood method implemented by the Palamedes toolbox in Matlab (Prins & Kingdom, 2018). The slope, threshold, lapse rate and guess rate were free to vary. The values for the lapse and guess rate were constrained to lie between 0 and 0.06 following common guidelines (Wichmann & Hill, 2001). The functions were fitted accordingly for each participant, visibility condition and road environment of Experiment 2. From each function, we derived the point of subjective equality (PSE; i.e., the threshold, yielding 50% comparison vehicle faster responses) and the just noticeable difference (JND; i.e., the difference between the value that generated 75% and 25% of responses where the comparison vehicle was judged to be faster). To evaluate the goodness-of-fit of the fitted models we assessed each function's deviance, i.e., a statistic indicating the likelihood of the model relative to a saturated model fit (Wichman & Hill, 2001).

Following the preregistered exclusion criteria, participants were excluded from further analysis when a JND in one or more visibility or environment conditions indicated that the discrimination performance exceeded the range of displayed vehicle speeds, indicating that the participant was not able to perform the task properly (JNDs > 30 km/h; 12 participants in Experiment 1, 16 participants in Experiment 2). Participants were as well excluded when the assessed goodness-of-fit measure in one or more conditions indicated a significant deviance of the fitted model (*p* > .05; 13 participants in Experiment 1, 11 participants in Experiment 2; note that one participant in Experiment 1 and two participants in Experiment 2 met both exclusion criteria). The deviance for the remaining participants (Experiment 1: N = 80, 77% of all participants; Experiment 2: N = 31, 55% of all participants) indicated that the models fitted the data sufficiently well (Experiment 1: $M_{Deviance}$ = 3.35, $Max_{Deviance}$ = 10.84; Experiment 2: $M_{Deviance}$ = 3.48, $Max_{Deviance}$ = 10.10; all p > .05). The PSEs derived from the fitted functions were then entered into a repeated measures ANOVA to test the effects of visibility (Experiment 1 & 2) and road environment (Experiment 2) on the perceived speed. The ANOVA and planned contrasts were performed in R (R Core Team, 2017) using the *rstatix* (Kassambara, 2019) and *phia* packages (De Rosario-Martinez, 2015).

Data and analysis scripts are publicly available online (https://osf.io/k9w8q/).

3 Results

For each participant and visibility condition of Experiment 1, we fitted the psychometric functions and derived the PSEs, i.e., the 50% points of the fitted functions, as a measure for the perceived speed of the comparison vehicle relative to the standard. For reference, we show the fitted psychometric functions of the average responses in Figure 3. The PSEs derived from participants' individual fits are plotted in Figure 4. Comparing the PSEs across conditions with a repeated measures ANOVA revealed a significant effect of visibility on the perceived vehicle speed (F(3, 237) = 35.52, p < .001, η_p^2 = .31). The direction of this effect varied between the different contrast manipulations. The average PSE of the reduced contrast condition exceeded the PSE of the clear condition, indicating that the vehicles appeared to be slower when the contrast was reduced uniformly. Conversely, the PSEs of the low- and high-density fog conditions were lower than the PSE of the clear condition, indicating that the vehicles appeared to be faster when the contrast of the scene was reduced in a distance-dependent manner. Planned contrasts revealed a significant difference of the PSEs between the clear condition and reduced contrast condition (clear: *M* = 49.32 km/h, *SD* = 3.09 km/h; reduced contrast: *M* = 53.45 km/h, *SD* = 6.19 km/h; Bonferroni adjusted $p < .001$, $\eta_p^2 = .28$) as well as between the clear and low-density fog condition (low-density fog: *M* = 46.48 km/h, *SD* = 4.42 km/h; Bonferroni adjusted $p < .001$, $\eta_p^2 = .24$), but not between the clear and high-density fog condition (high-density fog: *M* = 47.95 km/h, *SD* = 6.18 km/h; Bonferroni adjusted $p = .304$, $\eta_p^2 = .04$) or between the low-density and high-density fog condition (Bonferroni adjusted $p = .168$, $\eta_p^2 = .05$).

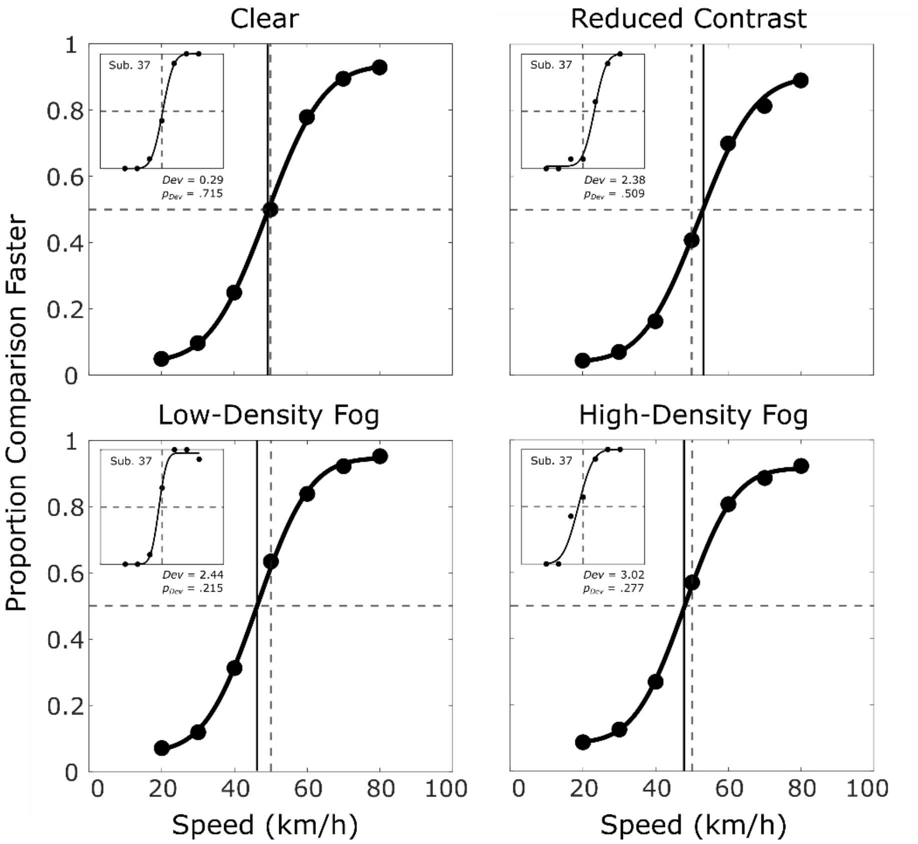

Figure 3. Cumulative Gaussian functions fitted through the mean response data of all participants (N = 80) of Experiment 1. Dots depict the mean proportion of the comparison vehicle faster responses. Black lines indicate the PSEs of the fitted functions, i.e., the 50% point of the function. A PSE above or below 50 km/h indicates that the speed of the comparison vehicle was under- or overestimated relative to the clear standard. Insets show the individual fits of a representative exemplar participant, given their bias and goodness-of-

fit statistics. Note that the psychometric fits based on the sample average are shown here for reference only. All statistics are based on the *individual* psychometric fits.

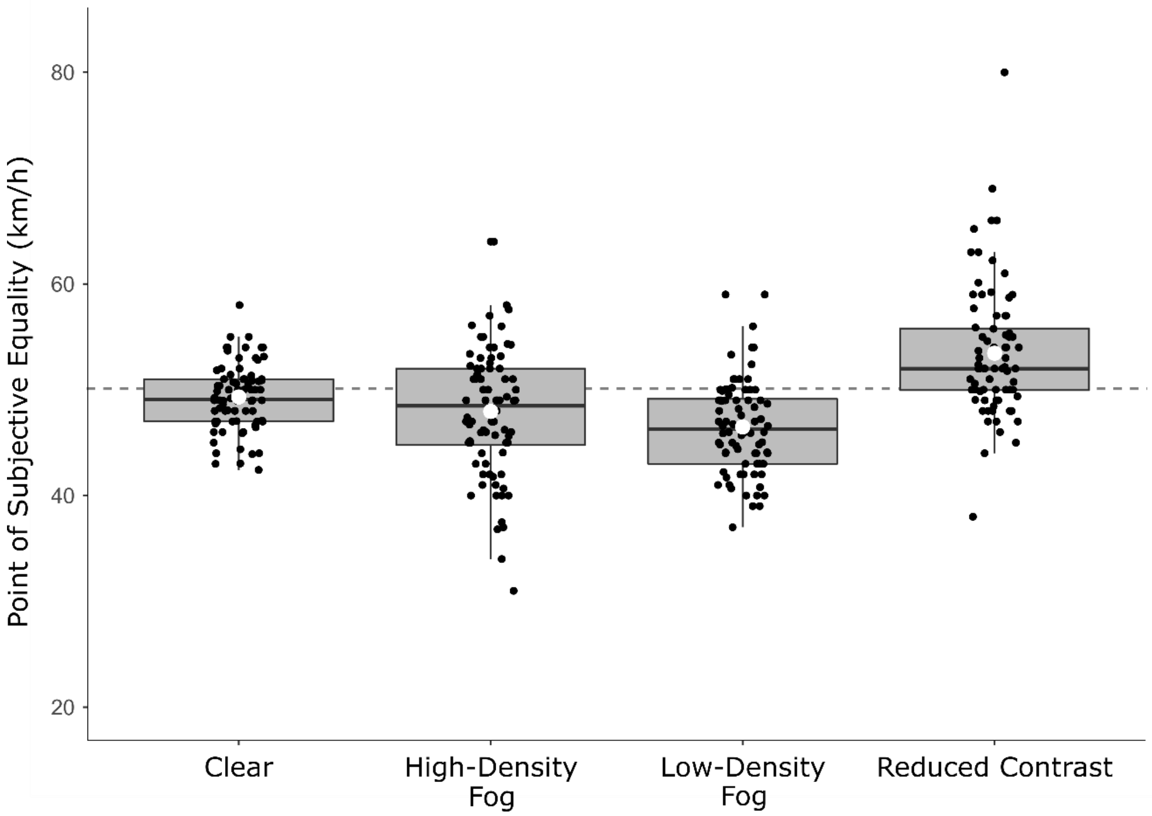

Figure 4. Points of subjective equality (PSEs) of participants in Experiment 1 (N = 80). Individual data points represent the PSEs derived from the psychometric functions of each participant and visibility condition. Crossbars and white dots depict the median and mean across participants. Whiskers depict the 1.5 x interquartile ranges.

In Experiment 2, we fitted the psychometric functions for each participant, visibility condition and road environment. Figure 5 shows the fitted psychometric functions of the average responses. The PSEs for each participant, visibility condition and road environment that were derived from the individual fits are shown in Figure 6. The repeated measures ANOVA performed on the PSEs showed significant main effects of both the visibility ($F(1, 30) = 19.91$, $p < .001$, $\eta_p^2 = .40$) and the road environment ($F(2, 60) = 20.82$, $p < .001$, $\eta_p^2 = .41$), but no interaction effect ($F(2, 60) = 0.33$, $p = .719$, $\eta_p^2 = .01$). For a more detailed analysis, we analyzed the simple effects via planned contrasts. Comparing the fog and clear view condition separated by the three road environments confirmed that in all tested environments the perceived speed increased during simulated fog as indicated by the overall lower PSEs in the fog conditions (clear: *M* = 51.71 km/h, *SD* = 4.39 km/h; fog: *M* = 47.12 km/h, *SD* = 5.81 km/h; clear, trees: *M* = 47.09 km/h, *SD* = 4.46 km/h; fog, trees: *M* = 43.36 km/h, *SD* = 5.32 km/h; clear, markings *M* = 46.97 km/h, *SD* = 4.08 km/h; fog, markings: *M* = 43.49 km/h, *SD* = 3.83 km/h; all Bonferroni adjusted *p*s < .021, $\eta_p^2 > .22$). Moreover, under both visibility conditions, the comparison with the original traffic scene showed that the perceived speed increased when trees or road markings were added to the scene (all Bonferroni adjusted *p*s < .019, $\eta_p^2 > .25$), whereas the comparisons between the tree and marking conditions yielded no significant differences (all *p*s > .890, $\eta_p^2 < .01$).

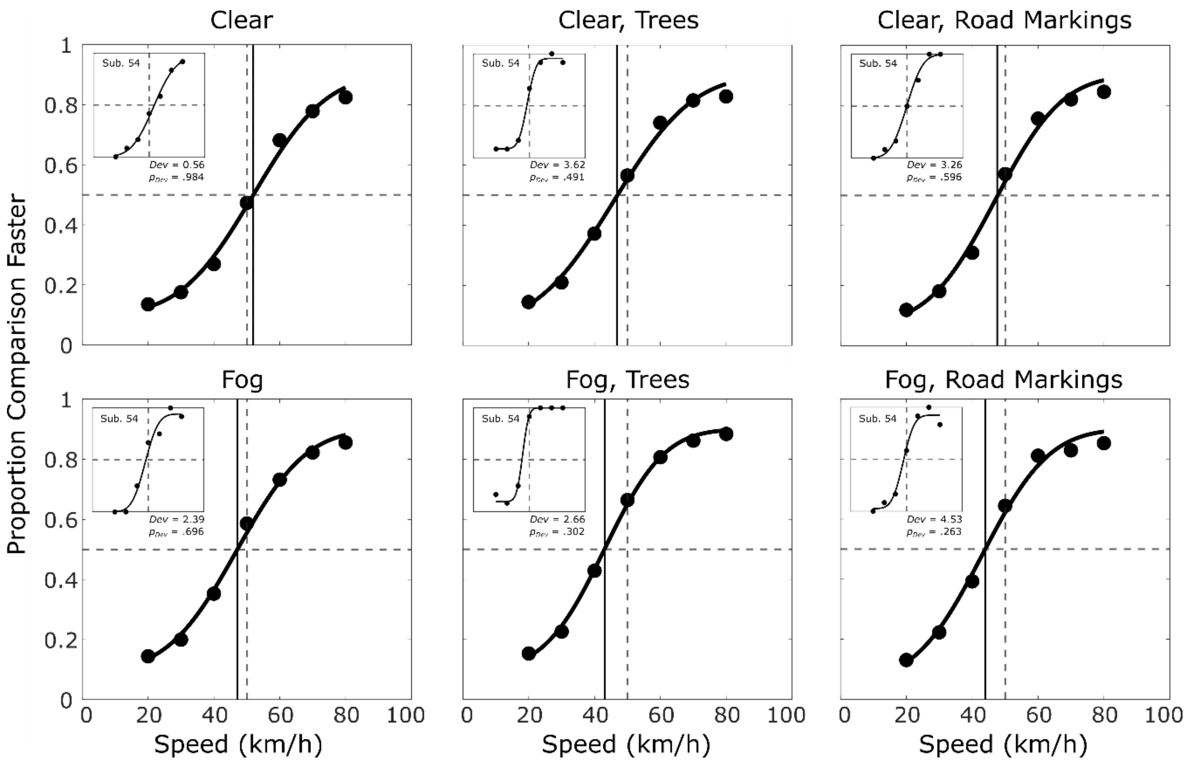

Figure 5. Cumulative Gaussian functions fitted through the mean response data of all participants (N = 31) of Experiment 2. Dots depict the mean proportion of the comparison vehicle faster responses. Black lines indicate the PSEs of the fitted functions, i.e., the 50%

point of the function. A PSE above or below 50 km/h indicates that the speed of the comparison vehicle was under- or overestimated relative to the speed of the clear view standard that did not depict road markings or trees. Insets show the individual fits of a representative exemplar participant, given their bias and goodness-of-fit statistics. Note that the psychometric fits based on the sample average are shown here for reference only. All statistics are based on *individual* psychometric fits.

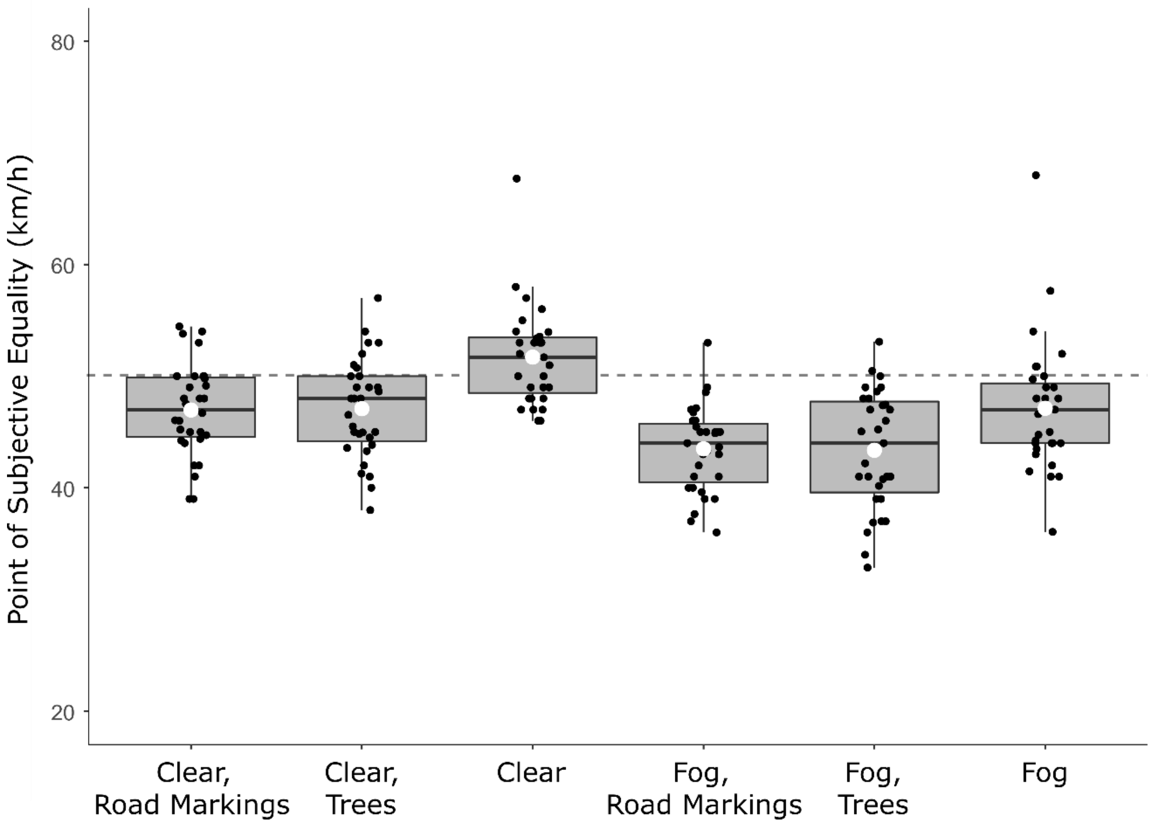

Figure 6. Points of subjective equality (PSEs) of participants in Experiment 2 (N = 31). Individual data points represent the PSEs of each participant in each visibility and environment condition. Crossbars and white dots depict the median and mean across participants. Whiskers depict the 1.5 x interquartile ranges.

4 Discussion

By manipulating the visual contrast at a virtual road crossing, we tested the effects of visibility on the perceived vehicle speed from a pedestrian's point of view.

Our first experiment tested the effect of different contrast distributions on the perceived vehicle speed. The results show that the perceived speed can both increase or decrease depending on the spatial distribution of contrast. As expected, when the contrast of our scene was reduced uniformly, observers underestimated vehicle speed compared to the same vehicle with no reduction in contrast. Our results thereby replicate in a road-crossing scenario previous studies showing that a uniform reduction of contrast is likely to decrease the perceived speed of moving stimuli (Blakemore & Snowden, 1999; Brooks, 2001; Champion & Warren, 2017; Moscatelli et al., 2019; Stone & Thompson, 1992; Thompson, 1982). There are various explanations for the underestimation of speed at low contrast. Bayesian accounts for the effect propose that the underestimation of speed results from the influence of a slow-motion prior that compensates for the uncertainty of the velocity signal at low contrast (Weiss, Simoncelli & Adelson, 2002; Stocker and Simoncelli, 2006). While the predictions from this account hold true at relatively slow stimulus speeds, i.e., typically below 8 deg/s, evidence in conflict with the Bayesian account comes from the finding that a uniform reduction of contrast can as well *increase* the perceived speed of stimuli that have higher retinal velocities (e.g., Thompson, Brooks & Hammett, 2006; Hassan & Hammett, 2015). Alternatively, Thompson et al. (2006) proposed a ratio model that can account for both speed over- and underestimation at low contrast. The model suggests that the effect of contrast arises from deriving speed as the ratio between the activity of low-pass and band-pass temporally filtered channels. As contrast affects the relative activity of each channel, reducing contrast changes the response ratio, in such a way that the perceived speed decreases with low contrast at lower temporal frequencies and increases with low contrast at higher temporal frequencies. In typical road-crossing situations, when vehicles are viewed from the edge of a road approaching from afar, vehicle motion would usually correspond to relatively slow retinal velocities, for which both accounts (the Bayesian account and the ratio model) would therefore predict a decrease of the perceived speed, which is in line with the results of our present study. In road traffic, a global reduction of contrast, for example, due to individual visual impairments affecting retinal image contrast, could thus present a specific safety risk. While previous research has already highlighted these risks in the context of driving by showing that drivers tend to underestimate their driving speed and, consequently, choose higher speed levels when the contrast of their view is globally reduced (Horswill & Plooy, 2008; Pretto et al., 2012; Snowden et al., 1998), the present results now demonstrate how this bias can as well compromise pedestrians' speed judgements of approaching vehicles. Note however, that the experiment which employed the uniform contrast reduction was conducted remotely. The differences in contrast between the conditions as reported in Table 1 can therefore only serve as a reference for the actual contrasts as depicted on participants' screens. While this does not limit the interpretation of our results in terms of their direction, the specific extent of contrast-related changes in the perceived vehicle speed remains subject to further investigation under more controlled viewing conditions. It further remains to be tested, whether and how a bias in the perceived vehicle speed due to a uniform reduction of contrast would translate to real-world navigational behavior, for example, crossing-decisions. Research on drivers with cataracts show that drivers are likely to adopt self-regulating strategies, such as choosing lower driving speeds to compensate for the experienced increase in driving difficulty (Ortiz-Peregrina, Ortiz, Martino, Casares-López, Castro-Torres & Anera, 2022). It could be that similar strategies are as well employed by pedestrians.

Our results, however, also make it clear that a transfer of these findings to other types of visibility restrictions, such as in adverse weather conditions, does not necessarily apply. When we simulated visibility in fog by reducing the contrast of our scene in a distance-dependent manner, the perceived speed increased compared to the speed of the same vehicle shown under clear view conditions. An increase of the estimated vehicle speed was observed both when the perceived speed was tested remotely and under more controlled viewing conditions. The bias also persisted when we simulated fog in different road environments. While it is conceivable that observers added a safety margin to the estimated vehicle speed to compensate for the higher uncertainty of the speed signal experienced in fog, we would have then expected a similar strategy to be employed under a uniform contrast reduction. This was found to not be the case. We therefore favor an interpretation of the fog-induced increase of the perceived speed as a perceptual effect. We hereby show that speed judgments of vehicles viewed from a pedestrian's perspective suffer from a similar fog-induced bias as self-motion judgements during driving (Pretto et al., 2012), although both types of judgements typically draw on different visual motion cues. While the integration of motion signals across the visual field provides a potential explanation for the perceptual bias of drivers experienced in fog, it cannot account for the increase of the perceived vehicle speed observed in the present study, i.e., unlike in driving where proximal cues from the periphery can account for the effect, the distinction between peripheral and central optic flow has little relevance when assessing the speed of approaching vehicles.

Alternatively, various interpretations of the effect of fog on pedestrians can be entertained. It could be that the increase of the perceived speed in fog was caused by an overestimation of vehicle distance. Fog has been shown to increase the perceived distance of vehicles (Cavallo, Colomb & Doré, 2001; Dong, Chen, Zhang, Zhang, Zhang & Zhang, 2021) and other objects (Ross, 1967). Among other things, the bias can be attributed to the intensification of the aerial perspective resulting from the distance-dependent changes of color and contrast. Moreover, the height of an object in the visual field can serve as a cue to distance (Cutting & Visthon, 1995). As the color of the horizon and distant environment became more similar under foggy conditions in our scenes, the horizon may have been misplaced and perceived as being lower. Vehicles in fog may have therefore appeared to be closer to the horizon, potentially contributing to the impression that vehicles in fog were farther away. As vehicles that are farther away would need to drive at higher physical speeds to produce the same retinal speeds as vehicles closer to the observer, an overestimation of vehicle distance could lead to an overestimation of vehicle speed if observers used the perceived distance to scale the retinal speed signal (Epstein, 1978; Rock, Hill & Fineman, 1968). The relevance of distance perception for speed scaling, however, remains subject to debate and some studies fail to document a direct relationship between perceived distance and perceived speed (McKee & Welch, 1989; Zohary & Sittig, 1993). On the other hand, visually rich environments can improve the accuracy of speed judgements, presumably due to providing reference points to the relative position of an approaching object (e.g., Rushton & Duke, 2009). Typical road environments encountered by pedestrians are unlikely to be as deprived of visual features as the original traffic scene that we presented. If the increase of the perceived speed in fog occurred due to a biased perception of distance, we assumed that increasing the availability of reference points by adding road markings or roadside trees could potentially reduce the fog-induced speed bias. When we tested the effect of fog in different road environments, however, the addition of equally spaced road markings or roadside trees to our scene did not reduce the perceived speed difference between the clear and fog condition. In all tested environments, a distance-dependent contrast reduction resulted in higher speed estimates and we found no interaction between visibility and the road environment. Instead, the effects of fog and visual elements appeared to be additive, with both increasing the perceived speed relative to the clear view standard that provided no such reference points. We suppose that the increase of the perceived speed in the enriched road environments resulted from the addition of relative motion cues as vehicle motion was then viewed against the reference points. This interpretation would be in line with previous studies showing a similar increase of perceived speed with the addition of a static visual surrounding (e.g., Blakemore and Snowden, 2000, Brown, 1931, Gogel & McNulty, 1983, Nguyen-Tri & Faubert, 2007). In terms of the interpretation of the speed bias observed in fog, the fact that perceived speed increased in both simple and more enriched road environments suggests that a bias in the perceived vehicle distance may not be the primary driver.

Rather than originating from the spatial integration of the retinal speed signals across the visual field, as suggested for drivers, the effect of fog on the perceived speed could as well stem from the temporal integration of the motion signal across the vehicle's trajectory. Due to the simulated approach angle, the retinal speed of the vehicle increased continuously during the display interval. Simultaneously, as the vehicle moved through the fog, its visibility increased and as a result, the uncertainty of the motion signal decreased. In fog, observers may have thus based their judgements more on the higher retinal speed signals during the later trajectory of the vehicle, which could result in biased speed estimates towards higher vehicle speeds if the distance of the vehicle was not properly factored out. Using the retinal speed signal to estimate the actual driving speed without compensating for distance would continuously shift the perceived speed towards higher speed levels as the vehicle approaches the observer, reflecting a lack of speed constancy across the trajectory (Brown, 1931; McKee & Welch, 1989; Zohary & Sittig, 1993). Although observers are able to discriminate motion speeds of objects moving in depth (without necessarily relying on distance cues itself), perfect speed constancy is not always achieved (see McKee & Smallman, 1998 for review). As a result, closer objects can appear to move relatively faster than distant objects and distant objects can appear to move relatively slower than closer objects. While in the standard scene the uncertainty of the motion signal remained constant, the visibility in fog was considerably reduced during the early trajectory of the vehicle, masking specifically the slower retinal speed at the beginning of the interval. In trials with a high starting distance, the comparison vehicle might have even rendered invisible due to its low contrast against the background, reducing the overall visible part of its trajectory in fog. Integrating the retinal speed signal over the display interval could thus result in overall higher speed estimates under fog compared to clear view conditions if observers disregarded the early trajectory of the comparison vehicle and instead relied more on the later, higher retinal speeds as the vehicle became better visible. We would thus expect a relative overestimation of speed to occur whenever observers are prevented from viewing the early trajectory of the comparison vehicle, for example, when it is masked by low contrast, or when its display time is reduced to showing only the late trajectory. Future studies may evaluate this by systematically testing the prediction that the perceived speed would vary with the display interval.

One unexpected result was that increasing the fog density did not further increase the perceived speed. If the effect of fog is to reduce the weight of the (less visible) early part of the trajectory, we would have expected the perceived speed to increase with increasing fog-density as more of the early trajectory would have been discounted. However, the results showed little to no difference between the high- and low-density fog conditions. If anything, the results pointed towards a tendency for the perceived speed to slightly decrease with a higher fog density. We can only speculate on why this was the case. Figure 4 suggests that it could be the consequence of some outlying participants. We tested this by excluding all PSEs exceeding the 1.5 interquartile range within each condition. However, even if these values were removed, the perceived speed in the high-density fog condition did not exceed the perceived speed in the low-density fog condition. Alternatively, it might be that the depicted contrast differences between the two fog densities were simply not big enough to promote detectable differences in the perceived speed. As noted earlier, the remote online procedure did not allow us to recover the actual luminance contrasts as they appeared on participants' screens, which is a limitation future studies should overcome by testing the effects of different fog densities under more controlled viewing conditions.

Finally, we note that if the lack of speed constancy plays a role in the fog-induced bias, then the effect of fog would be specific to the perception of motion in depth and we would expect less of a bias when retinal velocity varies little across time, for example, when observing an object moving at a constant speed across the frontoparallel plane with the same contrast gradient. However, it is also conceivable that the dynamic change of contrast itself created the illusion that the vehicle was accelerating, i.e., as the contrast of the vehicle increased so did its perceived speed. Future studies may test this by investigating the effects of dynamic contrast changes for different trajectories and by assessing whether observers perceive the speed of a moving object that is subject to a gradual change in contrast as being constant.

Our study has some important limitations. Changing the contrast of our scene also affected its luminance, for example, the mostly white vehicle became darker and the relatively dark road became lighter. Our results could thus be confounded by the luminance changes of the contrast manipulated scenes. A decrease in luminance can result in an increase of perceived speed (e.g., Vaziri-Pashkam & Cavanagh, 2008, Pritchard & Hammett, 2012), which could account for the effect of fog, but not the effect of the uniform contrast reduction on the perceived vehicle speed. When the contrast of our scene was reduced uniformly, observers judged the speed of the darker comparison vehicle to be slower than the lighter, clear view standard, contradicting the assumption that the changes in the perceived speed in our scenes were merely due to the associated luminance changes. Nevertheless, for the interpretation of the results it is important to bear in mind that contrast-induced biases can vary with luminance (e.g., Hassan & Hammett, 2015), which was considerably lower in our screen-based experiments than would be expected in real-life settings The extent to which visibility constraints affect perceived vehicle speed may therefore vary from our present results depending on the very specific composition of the situation, such as vehicle color, ambient light, and brightness of the visual background and should ideally be tested under more realistic luminance conditions.

As noted earlier, we could not control for the actual luminance contrasts of Experiment 1 as depicted on the participants' individual display setup. Although we asked participants to perform the experiment in a dimly lit and undistracting environment, we also had no control over the conditions under which participants completed the study, which could have affected the luminance and contrast at which the videos were displayed. While this limits the interpretability of our results of the extent of the effects observed, it should not have affected the direction of the results pattern, such as the differences in the PSE depending on the spatial distribution of contrast (uniform vs. distance-dependent). Despite the less controlled testing conditions, we could replicate the findings of classical laboratory studies in terms of a uniform contrast reduction. Also, our second experiment, which was conducted in a more controlled environment and employed the same testing conditions for all participants, replicated the fog-induced increase of the perceived vehicle speed. This suggests that the effects were robust at least against the slight variations in the viewing conditions under which the stimuli were presented.

Finally, our study was limited to examining biases in relative speed judgements of a clear view standard and a contrast manipulated comparison. We can therefore not draw conclusions on the over- or underestimation of speed relative to the true speed of the vehicle. It further remains to be tested, if and how contrast-induced biases translate to pedestrians' decision-making. Previous research gives an indication that the contrast of a vehicle against its background affects crossing-decisions (Feldstein & Peli, 2020), but future studies may test this more systematically. Our results highlight the importance to then also take into consideration the effects of different contrast-distributions. Furthermore, the assumption that the integration of the motion signal across time could be decisive for the overestimation of vehicle speed in fog rests on the idea that the perceived speed changes with the distance of the vehicle and its retinal speed, which remains to be tested under more naturalistic conditions. A wider range of distance cues other than those provided by the additional environmental elements, may lead to better speed constancy (e.g., Distler, Gegenfurtner & van Veen, 2000) and could thus potentially reduce an effect of distance-dependent contrast reductions.

5 Conclusion

In two experiments, we tested the relation between visibility and perceived vehicle speed. Relative to a vehicle under clear visibility conditions, vehicle speed was underestimated when the contrast of the view was reduced uniformly but overestimated when vehicle contrast decreased with increasing distance to the observer. The relative speed overestimation of vehicles that were subject to a distance-dependent contrast reduction persisted, even when the road environment contained additional visual cues, such as equally spaced road marking or trees. The results demonstrate that a uniform reduction of contrast, for example, due to visual impairments affecting retinal image contrast, can compromise the safety of road users by decreasing the perceived speed of approaching vehicles. However, similarly to what has been noted for the perception of self-motion during driving, this bias does not necessarily translate to other visibility constraints, for example, to those experienced in adverse weather conditions such as fog. Instead, the perceived speed of vehicles depends on the spatial distribution of contrast and a reduction can both increase and decrease the perceived vehicle speed. Our results were gained from a virtual traffic scene depicting the view of a pedestrian as standing at the edge of a road at a crosswalk. However, it is likely that the biases extend to other road users when viewing approaching traffic from a similar perspective, for example, drivers waiting at an intersection. The origins of such misperceptions, especially the increase of vehicle speed in fog, remain unclear. We suspect that it could stem from the temporal integration of the motion signal in combination with a lack in speed constancy or from the illusion of an accelerating vehicle due its dynamic contrast-change, but both assumptions need further investigation.

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