Effect of Motorcycle Lighting Configurations on Drivers' Perceptions of Closing

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Abstract

Objective: The aims were to better understand how drivers perceive an approaching set of motorcycle headlights during nighttime driving and to determine whether alternative motorcycle headlight configurations improve drivers' perceptual judgments of closing for an oncoming motorcycle.

Background: Motorcyclists account for a disproportionate number of roadway fatalities, especially at night. One potential cause of this is drivers' misjudgments of a motorcycle's approach.

Method: The first experiment examined whether drivers were more sensitive to horizontal or vertical optical expansion and whether drivers could integrate these two dimensions to achieve a lower looming threshold. A second experiment built on these results to test whether alternative headlight configurations that maximized size were better than other motorcycle headlight configurations and a car's headlights. In both experiments, participants were instructed to press a button to indicate when they first perceived an oncoming vehicle to be closing under nighttime driving conditions.

Results: Headlight orientation did not affect when drivers perceived closing, and drivers were not able to integrate optical expansion from multiple dimensions in a way that achieves a lower looming threshold. However, the alternative motorcycle headlight configurations that accentuated the full extent of a motorcycle's size resulted in drivers perceiving closing sooner than other motorcycle headlight configurations but not sooner than as a car.

Conclusion: Drivers perceive closing sooner for larger headlight configurations unless the headlight configurations are relatively small.

Application: Drivers' perceptual judgments of motorcycles may improve when motorcycles have headlights that span its full height.

Keywords: vehicle design, nighttime visibility, vision, driver behavior, accident analysis.

1. Introduction

Motorcyclists account for a disproportionate number of roadway fatalities. Although motorcycles made up only 0.63% of total vehicle miles traveled in 2017, motorcyclists accounted for 13.92% of the 37,133 fatalities on the roadway, and the fatality rate per vehicle mile travelled was 27 times higher for motorcyclists compared to passenger car occupants (National Highway Traffic Safety Administration, 2019). Night driving is especially dangerous for motorcyclists because even though 35.96% of motorcycle crashes occur at night, this is when 49.00% of fatal motorcycle crashes occur (National Highway Traffic Safety Administration, 2020). This is likely because the entire motorcycle and rider is visible during daylight, but only the lights on the motorcycle are visible at night (Cavallo et al., 2015). Thus, the configuration of these lights is especially important for night driving.

Crashes between a motorcycle and another vehicle are often caused by the other vehicle violating the motorcycle's right-of-way such as when a vehicle pulls out in front of a motorcycle at an intersection (Hurt et al., 1981; Pai, 2011). One major cause of this is drivers' failures to detect the motorcycle because of its low conspicuity and relatively low frequency on the roadway, resulting in automobile drivers not expecting to see them (Hurt et al., 1981; Pai, 2011). However, even when drivers successfully detect the presence of a motorcycle, crash risk is not eliminated. In fact, drivers can violate a motorcycle's right-of-way and cause a crash if they misjudge the approach of an oncoming motorcycle. Such violations have been identified as another major cause of drivers violating a motorcycle's right-of-way (Pai, 2011) that occur about as often as detection failures (Maruyama et al., 2009). For example, prior research has shown drivers judged smaller vehicles (e.g., a motorcycle) as arriving later than larger vehicles (e.g., a full size car) even though they actually arrived at the same time (Caird and Hancock, 1994; Horswill et al., 2005), an effect known as the size-arrival effect (DeLucia, 1991, 2013; DeLucia & Warren, 1994). Such errors increase the likelihood of a crash in a left-turn-across-path scenario when the oncoming vehicle is a motorcycle compared to when the oncoming vehicle is a car or truck. These errors are likely exacerbated at night when the roadway is not illuminated and the motorcycle only has a standard single headlight configuration because the visual size of the motorcycle is comprised of only the size of the single headlight (Thomson, 1980). Alternative motorcycle lighting configurations may help drivers better judge the approach of an oncoming vehicle, which was the focus of the current research.

1.1 Alternative Motorcycle Lighting Configurations

Prior research on alternative motorcycle lighting configurations indicated that a larger lighting configuration improves drivers' judgments about the approach of an oncoming motorcycle in terms of speed discrimination (Gould et al., 2012a, 2012b) and gap acceptance (Cavallo et al., 2015; Tsutsumi and Maruyama, 2007). However, much of it lacked insight into whether drivers are equally sensitive to changes in size in the horizontal and vertical dimensions, which is important because drivers may be more sensitive to horizontal changes, but motorcycles are much narrower than other vehicles. Moreover, none of the prior research on motorcycle lighting configurations measured the effect of motorcycle lighting configurations on looming thresholds even though drivers use looming information, such as rate of optical expansion, to perceive the driving environment (Mortimer et al., 2014; Muttart et al., 2005). Consequently, one important theoretical question has not yet been adequately addressed: are drivers equally sensitive to horizontal and vertical optical expansion? If drivers are equally sensitive to both directions, then the logical conclusion would be to accentuate the longer dimension of the vehicle because optical expansion is larger for larger objects when all else is equal. However, Gould et al. (2012a) suggested that drivers are more sensitive to looming in the horizontal dimension, which would be particularly bad for motorcycles because they are so much narrower than other vehicles on the roadway. Gould et al. (2012a) found that a vertical motorcycle headlight configuration had a descriptively higher (i.e., worse) speed discrimination threshold compared to a horizontal motorcycle headlight configuration, providing some evidence for the hypothesis that drivers are more sensitive to looming along the horizontal dimension. These findings are seemingly at odds with basic perceptual research indicating that the size-arrival effect did not depend on orientation (DeLucia & Warren, 1994).

The current work posits one plausible theoretical explanation that accounts for both of these findings: drivers have undergone perceptual learning such that they have learned to base their perceptual judgments more on horizontal optical expansion than vertical optical expansion, causing an increase in sensitivity for optical expansion along the horizontal axis relative to the vertical axis. Because perceptual learning involves task- and stimuli-specific improvements (Goldstone, 1998), drivers' purported increased sensitivity to looming in the horizontal dimension would be specific to driving and not generalize to observers' perceptions more broadly.

Drivers may have learned to base their perceptual judgments more on horizontal optical expansion because they learned that there is less variability in the width of vehicles compared to the height of vehicles. For instance, the width of the Honda Civic, the most popular compact car in 2018 (Wardlaw, 2019), is 5.91 ft (Honda, n.d.), and the maximum width of commercial motor vehicles permitted by the Federal Highway Administration (2004) is 8.5 ft. However, the height of the Honda Civic is 4.58 ft (Honda, n.d.), and most states set height limits for commercial motor vehicles to 13.5 to 14 ft (Federal Highway Administration, 2004). Hence, the height of vehicles on the roadway varies much more than the width of vehicles on the roadway. In addition, headlights and taillights are located close to the sides of the vehicle, thereby accentuating the vehicle's width, but these lights often do not accentuate a vehicle's full height. Such a lighting configuration further increases the variability of the visual size of the height of vehicles but not the width. Consequently, drivers may become familiar with a vehicle's width because of its consistency, but this is not the case for the vehicle's height. The implication is that a vehicle's width provides the depth cue of familiar size, but its height does not provide this depth cue. Consequently, drivers may have learned to base their perceptual judgments on horizontal expansion more than vertical expansion. Indeed, drivers based their judgments more on horizontal expansion than vertical expansion (Muttart et al., 2005).

Although Gould et al. (2012a) suggested drivers are more sensitive to horizontal optical expansion, their results showed the difference between horizontally-oriented and vertically-oriented lighting configurations was not statistically significant; findings could have been due to either chance probability or to a real effect that went undetected by the statistical test due to insufficient statistical power. Further, Gould et al. (2012a) measured drivers' speed discrimination thresholds instead of drivers' looming thresholds. The current research aimed to address the theoretical question of whether drivers are equally sensitive to horizontal and vertical optical expansion by measuring drivers' optical expansion rate thresholds to horizontally-oriented and vertically-oriented headlights on a motorcycle with enough participants to ensure adequate power.

1.2 Achieving a Lower Threshold with Vertical and Horizontal Dimensions

Another theoretical question that is particularly relevant to judging the approach of an oncoming motorcycle is whether drivers can achieve a lower looming threshold when both the horizontal and vertical dimensions are visible simultaneously compared to when only one of these dimensions is visible. This question is relevant because if drivers can achieve a lower optical expansion threshold when both are visible, both dimensions should be accentuated by a motorcycle's lighting configuration to maximize drivers' ability to perceive them accurately and sooner at night. On the other hand, if drivers cannot achieve a lower optical expansion threshold when both are visible, only one dimension needs to be accentuated with lights, and with fewer lights, the motorcycle lighting configuration would cost less. Even if drivers base their perceptual judgments on horizontal optical expansion more than vertical optical expansion as previously suggested by the perceptual learning explanation, drivers could still integrate vertical optical expansion with horizontal optical expansion to achieve a lower threshold. Thus, the perceptual learning explanation only predicts that drivers will not base their perceptual judgments upon only vertical optical expansion when all other factors are kept constant (e.g., size of the horizontal and vertical dimension). However, prior research offers more specific predictions.

Gould et al. (2012a) compared horizontally-oriented and vertically-oriented motorcycle headlight configurations to a triangular motorcycle headlight configuration. Speed discrimination was better for the triangular configuration compared to the vertical configuration, but the difference between the triangular and horizontal configurations was not statistically significant. Consequently, it is unclear whether drivers integrate horizontal and vertical optical expansion or base their perceptual judgments upon one dimension alone. Further complicating the interpretation of these results, the triangular lighting configuration had a different height than the vertical configuration, which introduced a confound of size.

Mortimer (1970) also examined whether lighting configurations that have both width and height affect when drivers perceive closing, but he focused on the taillight configuration of cars instead of motorcycles. Drivers perceived closing sooner for cars with combined horizontal-vertical taillight configurations compared to horizontal-only taillight configurations, suggesting that drivers can integrate horizontal and vertical optical expansion to achieve a lower threshold. However, taillight configuration was confounded with the number of taillights and the total luminous flux from the taillights because the number of taillights and total luminous flux from the taillights systematically varied with the taillight configurations. Therefore, it cannot be determined whether the results were due to a change in the horizontal and vertical dimensions, the number of taillights, or the total luminous flux. Additionally, Mortimer did not have a vertical-only taillight configuration condition, and thus could not tease apart the effect of only the vertical dimension from the effect of both the horizontal and vertical dimensions. The current research aimed to address the shortcomings of Gould et al. (2012a) and Mortimer (1970) by comparing the optical expansion rate thresholds for a horizontal headlight configuration, vertical headlight configuration, and combined horizontal-vertical headlight configuration while controlling for size, number of headlights, and total luminous flux from the headlights.

1.3 Current Studies

Broadly, the aims of the current studies were to better understand how drivers perceive an approaching set of motorcycle headlights and to determine whether alternative motorcycle headlight configurations improve drivers' perceptual judgments of closing for an oncoming motorcycle. A key contribution of the current research was to examine whether drivers were more sensitive to horizontal optical expansion compared to vertical optical expansion, which would be consistent with the notion that drivers have undergone perceptual learning. Further, the current work examined whether drivers achieve a lower looming threshold when the horizontal and vertical dimensions are both visible compared to when only one of these dimensions is visible. Finally, the resulting alternative motorcycle headlight configurations were compared to other motorcycle headlight configurations and a car's headlights. Results have implications for motorcycle headlight design.

2. Experiment 1

The current research addressed two research questions in Experiment 1: (1) Are drivers equally sensitive to horizontal and vertical optical expansion? (2) When the horizontal and vertical dimensions are both visible, are drivers able to achieve a lower looming threshold compared to when only the horizontal dimension or only the vertical dimension is visible? It was hypothesized that drivers would be more sensitive to horizontal optical expansion (hypothesis 1), and that drivers would achieve a lower looming threshold when both horizontal and vertical optical expansion is available compared to when only one of these dimensions is available (hypothesis 2).

2.1 Method

2.1.1 Participants

Based on a priori power analyses to detect effect sizes similar to Gould et al. (2012a) with a power of at least 0.90 (see Supplemental Materials), 35 people (21 female) participated (without counting outliers) and were compensated with $15 Amazon gift cards. Age ranged from 19 to 70 years (M = 34.57, SD = 12.86). All participants held a driver's license from 1 to 56 years (M = 18.00, SD = 13.39). Almost all of the participants (n = 33) reported no recent experience with driving a motorcycle. All but one of the participants reported normal or corrected visual acuity. The one participant who did not have normal or corrected visual acuity reported their eye doctor advised them their visual acuity was not poor enough to require corrective lenses; additionally, this participant indicated they could see the screen clearly. This research complied with the American Psychological Association Code of Ethics and was approved by the Institutional Review Board at Rice University. Informed consent was obtained from each participant.

2.1.2 Apparatus and Displays

The roadway scenes were created using the STISIM Drive driving simulator (Systems Technology, 2016). STISIM Drive has been described as a medium fidelity driving simulator that provides a realistic roadway environment (Braly et al., 2018; Freund et al., 2005; Levulis et al., 2015). E-Prime 3.0 (Psychology Software Tools, 2016) and E-Prime Go (Psychology Software Tools, 2020) were used to present video recordings of the roadway scenes to participants on their own computer and record their button-press response. Participants downloaded the needed experimental files at the beginning of the experiment so that E-Prime Go could display the roadway scene videos without buffering and accurately record response time. For all participants, the display subtended 45° of visual angle horizontally. This was achieved by having participants measure the width of their screens, which the experimenter would then use to calculate the correct viewing distance.

Each scene consisted of a flat, two-way road with one lane in each direction and a two-way left turn lane in the middle. To emulate nighttime driving scenarios, the ambient lighting setting was set to 5% and the diffuse and specular lighting settings were set to 0% for all roadway scenes, consistent with occupational therapy work with nighttime driving conducted by the developers of STISIM Drive (T. J. Rosenthal, personal communication, August 17, 2020). Almost all of the participants (n = 33) reported the roadway scenes accurately reflected the dark lighting conditions of nighttime driving on a rural highway with no streetlights. There were three motorcycle headlight configurations that were replicated eight times each, producing 24 roadway scenes that were presented in a random order.

To emulate a typical scenario in which a driver would violate the motorcycle's right of way, the participant's vehicle was stopped in a two-way left turn lane at an intersection as if they were going to turn left, and a motorcycle was approaching in the oncoming lane at a constant velocity of 30 mph (48.28 km/h) as shown in Figure 1. When the scene started, the oncoming motorcycle was 750 to 850 ft (228.60 to 259.08 m; randomly selected for each scene) from the participant. Participants were instructed to press a button on their keyboard as soon as they perceived the oncoming motorcycle was getting closer to them (i.e., when they first perceived closing). The time at which participants pressed the button was recorded by the E-Prime Go software (Psychology Software Tools, 2020) and was used to derive the oncoming vehicle's optical expansion rate, the dependent variable of interest. To address the theoretical aspects of the research questions, only the headlights of the oncoming motorcycle were visible to the participant. Hence, the participant's vehicle's headlights were not turned on, consistent with prior research (Gould et al., 2012a).

2.1.3 Motorcycle Headlight Configurations

There were three motorcycle headlight configurations: horizontal (Figure 2A), vertical (Figure 2B), and combined (Figure 2C). To control for confounds between configuration and other factors (number of lights, total luminous flux, size), all three headlight configurations had four circular headlights of equal size (3.94 in [10 cm] diameter, consistent with the smaller lights from Gould et al. [2012a]); this kept the number of headlights and total luminous flux constant across configurations. To control for size, the width of the horizontal configuration, the height of

Figure 1

Conceptual Representation of the Driving Scenario with Participant's Vehicle Stopped in a Two-Way Left Turn Lane and Motorcycle Travelling in Oncoming Lane

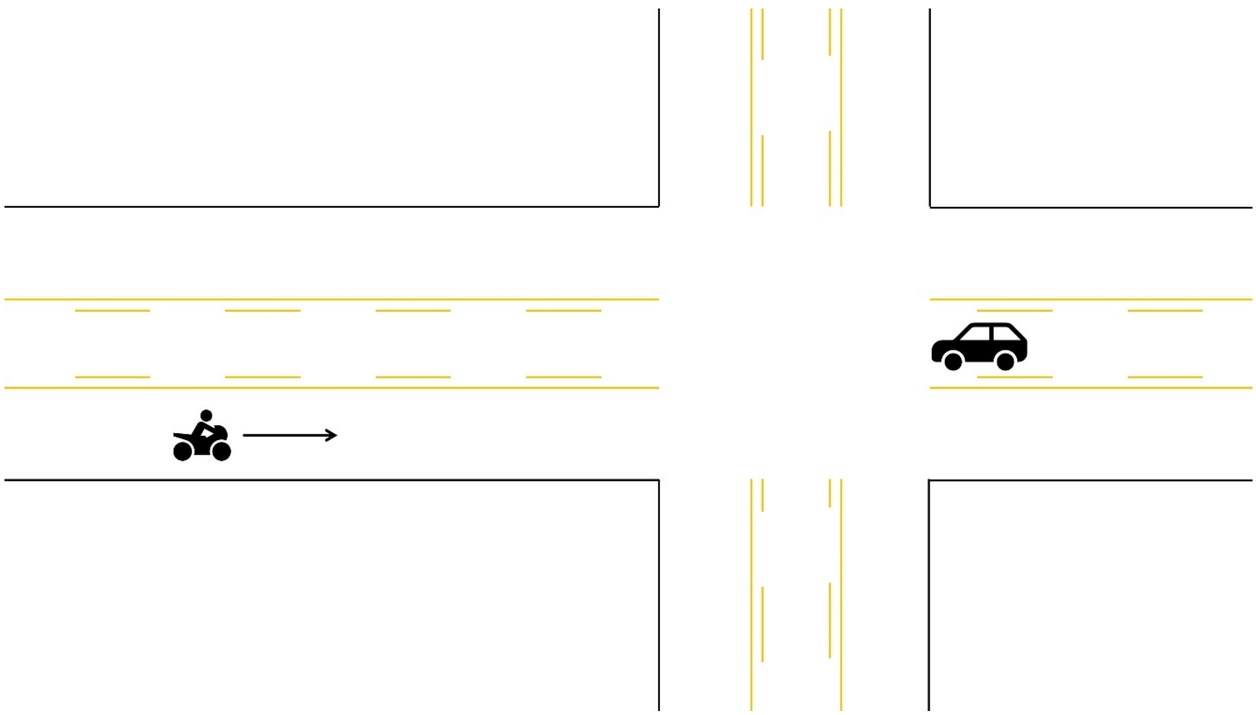
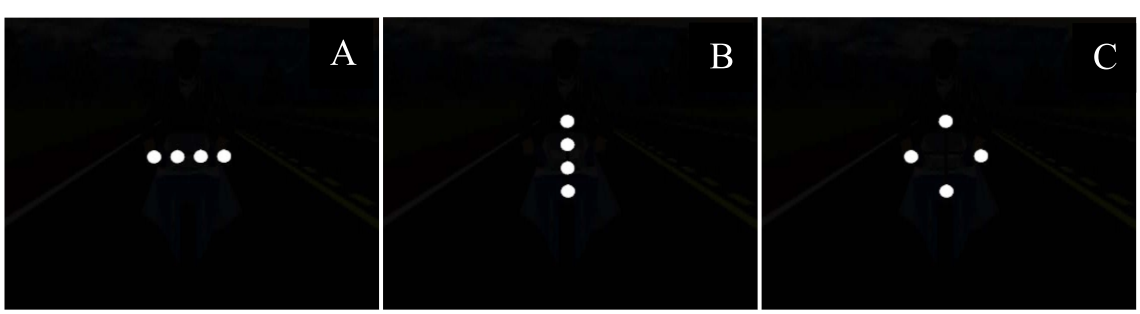


Figure 2

Experiment 1 Motorcycle Headlight Configurations Under Nighttime Conditions



Note. The headlight configurations are on the same scale. Configurations shown: Horizontal (A), Vertical (B), and Combined (C).

the vertical configuration, the width of the combined configuration, and the height of the combined configuration were kept constant at 2 ft (0.61 m).

2.1.4 Procedure and Design

To start, participants joined a Zoom video call live with the experimenter. To achieve as much consistency as possible in the remote setting and to enable the participants to see the roadway scenes effectively, participants were asked to darken their room as much as possible. Participants completed a practice trial with each headlight configuration and then the 24 experimental roadway scenes. All participants experienced all of the motorcycle lighting configurations. Afterwards, they completed a post-study questionnaire through Qualtrics.

2.2 Results

There is a delay between the moment a driver perceives closing and the moment the driver presses a button. This delay is known as perception-response time (PRT; Muttart et al., 2005; Weaver et al., 2021). Consistent with prior research (Muttart et al., 2005; Weaver et al., 2021), a PRT of 1.6 s was used, meaning 1.6 s was subtracted from the time of the button press before calculating the optical expansion rate (Muttart et al., 2005, Equation 1). If a participant responded less than 1.6 s into the roadway scene, that trial was removed from data analysis, and if a participant had one or more missing cells from too many trials with a response time of less than 1.6 s, that participant was replaced. This resulted in one participant being replaced and 10 total trials (1.19%) from the remaining 35 participants being removed. Given the nighttime driving environment, the size of the headlights—in particular, the longer dimension of the headlight—was used for the size when calculating optical expansion rate, which was 2 ft (0.61 m) for all the configurations in the current experiment.

For all analyses in the current paper, the significance level was set to .05. Prior to any inferential statistics, the data was checked for outliers based on whether any participants had mean optical expansion rates more extreme than ±3 standard deviations from the mean (Kannan et al., 2015). Using this method, five participants were identified as outliers and replaced. Shapiro-Wilk tests indicated the mean optical expansion rate significantly deviated from normally distributed for all three pairwise differences, but the sample size for the current experiment ($n = 35$) is large enough that this violation of the normality assumption is not of concern (Ghasemi & Zahediasl, 2012). Effect size is reported using Cohen's d_z for within-subjects comparisons and Cohen's *d* for between-subjects comparisons; an effect size of 0.2, 0.5, and 0.8 reflects a small, medium, and large effect size, respectively (Cohen, 1988).

For the first research question, a paired samples *t*-test indicated the mean optical expansion rate was not significantly different between the horizontal headlight configuration ($M = 0.000279$, $SD = 0.000108$ rad/s) and vertical headlight configuration ($M = 0.000265$, $SD = 0.000085$ rad/s), $t(34) = 1.44$, $p = .156$, $d_z = 0.243$. This result does not support the first hypothesis that drivers would be more sensitive to horizontal optical expansion compared to vertical optical expansion.

For the second research question, paired samples *t*-tests indicated the mean optical expansion rate was not significantly different between the vertical headlight configuration and the combined headlight configuration ($M = 0.000257$, $SD = 0.000082$ rad/s), $t(34) = 1.23$, $p = .226$, $d_z = 0.208$, but the mean optical expansion rate was significantly smaller for the combined headlight configuration compared to the horizontal headlight configuration, $t(34) = 2.30$, $p = 0.028$, $d_z = 0.389$. These results do not support the second hypothesis. However, when these results were analyzed without replacing outliers, they changed such that the mean optical expansion rate was significantly smaller for the combined headlight configuration compared to both the vertical headlight configuration and the horizontal headlight configuration; this is discussed later.

2.3 Discussion

The first hypothesis that drivers are more sensitive to horizontal optical expansion than vertical optical expansion was not supported. This contradicts the suggestion made by prior research (Gould et al., 2012a) that drivers are more sensitive to looming along the horizontal axis relative to the vertical axis. Theoretically, this finding suggests that drivers have not undergone perceptual learning for the task of judging closing on the roadway in such a way that drivers base their perceptual judgments on looming in the horizontal direction more than the vertical direction. Practically, this means that, when all else is kept constant, the orientation of a headlight configuration does not affect when drivers perceive closing.

The second hypothesis that drivers achieve a lower looming threshold when both horizontal and vertical optical expansion is available was not supported. Theoretically, this suggests that drivers could not integrate looming from the horizontal and vertical dimensions in a way that achieves a lower looming threshold and instead used looming primarily along the vertical dimension. This finding is inconsistent with the perceptual learning explanation that drivers base their perceptual judgments on looming in the horizontal direction more than the vertical direction. Practically, these results in conjunction with the finding that drivers are equally sensitive to looming along the horizontal and vertical axes mean only the vertical dimension of a motorcycle needs to be accentuated to improve driver's perceptual judgments of closing. Accordingly, the subsequent experiment tested a motorcycle headlight configuration that accentuated the full extent of the motorcycle's vertical dimension including the motorcyclist.

When the results for the second hypothesis were analyzed without replacing outliers, the mean optical expansion rate for the combined configuration was significantly smaller than both the horizontal headlight configuration and the vertical headlight configuration, supporting the second hypothesis, contrary to the analysis that replaced outliers. Although more credence should be given to the analyses that replaced outliers because outliers may represent participants that did not understand or follow the instructions, these results were taken into consideration when designing the motorcycle headlight configurations for the subsequent experiment, which included a headlight configuration that accentuated the full extent of the motorcycle's combined vertical and horizontal dimensions.

3. Experiment 2

Experiment 2 examined how motorcycle headlight configurations that maximize its size affect drivers' perceptions for closing because optical expansion is larger for larger objects when all else is equal. Accordingly, Experiment 2 was aimed at benchmarking how good a motorcycle with a fully accentuated vertical headlight configuration and a motorcycle with a fully accentuated combined headlight configuration are compared to (a) a motorcycle with a standard single headlight, (b) a motorcycle with a tri-headlight configuration, and (c) a car. In particular, the current experiment aimed to answer whether the looming threshold for closing and when drivers perceive closing is different for a car, a motorcycle with a single headlight, a motorcycle with a tri-headlight configuration, a motorcycle with a fully accentuated vertical headlight configuration, and a motorcycle with a fully accentuated combined headlight configuration under nighttime conditions with the participant vehicle's headlights turned on.

In prior research, the looming threshold for closing was smaller for cars compared to motorcycles (Gould et al., 2013), though this was during daytime conditions, suggesting that the visible size of the approaching vehicle affects the looming threshold for closing. It was hypothesized that drivers are more sensitive to larger headlight configurations compared to smaller headlight configurations (hypothesis 1). The dependent measure used to evaluate this hypothesis was optical expansion rate of the oncoming vehicle's headlights. As the size of the approaching object increases and as the optical expansion rate at threshold decreases, the longitudinal bumper-to-bumper distance when the driver perceives closing increases. It was hypothesized that drivers perceive closing sooner for larger headlight configurations compared to smaller headlight configurations (hypothesis 2). The dependent measure used to evaluate this hypothesis was longitudinal bumper-to-bumper distance between the participant's vehicle and the oncoming vehicle.

3.1 Method

The methods for Experiment 2 were identical to Experiment 1 except that the participant's vehicle had their headlights turned on to align more with actual nighttime driving and there were five oncoming vehicle headlight configurations (all different from Experiment 1). With five oncoming vehicles, there were 40 experimental roadway scenes (eight replicates per vehicle).

3.1.1 Participants

Thirty-five people (25 female) participated (without counting outliers) and were compensated with $15 Amazon gift cards. Age ranged from 18 to 53 years (M = 28.49, SD = 9.73). All participants held a driver's license from 1 to 37 years (M = 11.17, SD = 9.71). Almost all of the participants (n = 33) reported no recent experience with driving a motorcycle. All participants reported normal or corrected visual acuity. This research complied with the

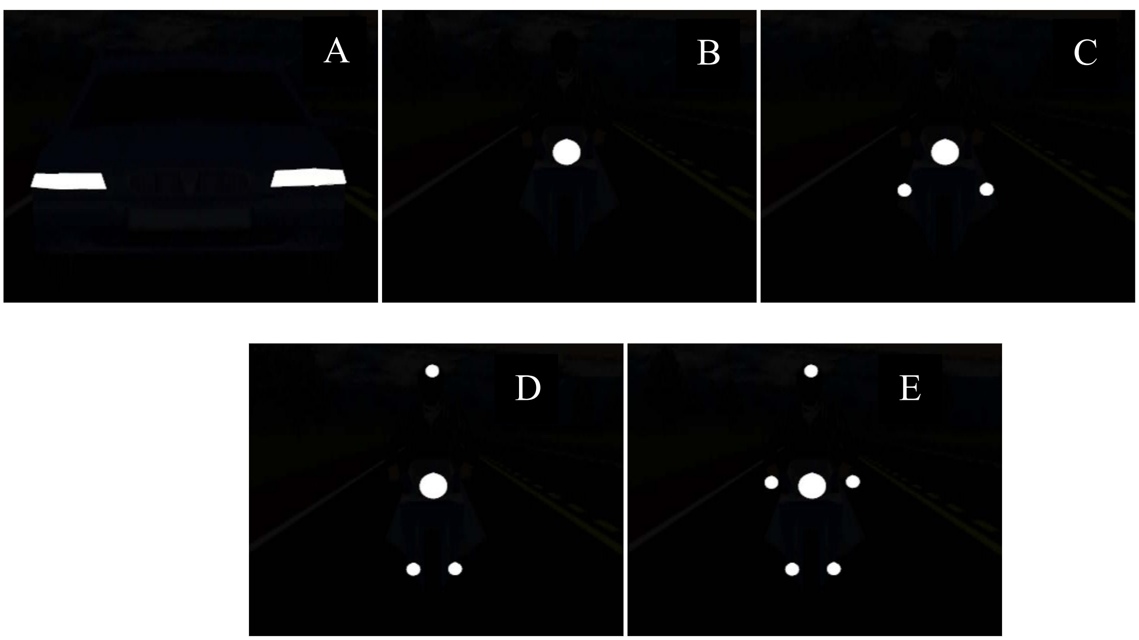
American Psychological Association Code of Ethics and was approved by the Institutional Review Board at Rice University. Informed consent was obtained from each participant.

3.1.2 Oncoming Vehicle Headlight Configurations

The five oncoming vehicles were a car (Figure 3A), a motorcycle with a single headlight configuration (Figure 3B; a “standard” configuration; Gould et al., 2012a), a motorcycle with a tri-headlight configuration (Figure 3C; Gould et al., 2012a), a motorcycle with a fully accentuated vertical headlight configuration (Figure 3D; Cavallo et al., 2015), and a motorcycle

Figure 3

Experiment 2 Oncoming Vehicle Headlight Configurations Under Nighttime Conditions



Note. The headlight configurations are on the same scale. Configurations shown: Car Headlight Configuration (A), Motorcycle with Single Headlight Configuration (B), Motorcycle with Tri-Headlight Configuration (C), Motorcycle with Fully Accentuated Vertical Headlight Configuration (D), and Motorcycle with Fully Accentuated Combined Headlight Configuration (E).

with a fully accentuated combined headlight configuration (Figure 3E; Cavallo et al., 2015). The car's headlight configuration was 3.6 in (9.14 cm) tall and 5.9 ft (1.80 m) wide. For all of the motorcycle headlight configurations, there was a main circular headlight with a diameter of 7.87 in (20 cm), and for the motorcycle configurations that had additional circular headlights, these headlights had a diameter of 3.94 in (10 cm), consistent with Gould et al. (2012a). Accordingly, the width and height of the single motorcycle headlight configuration was 7.87 in (20 cm). The tri-headlight configuration had two smaller headlights below the main headlight, resulting in a width of 2.30 ft (0.70 m) and a height of 1.38 ft (0.42 m). For the fully accentuated vertical motorcycle headlight configuration, headlights were mounted on the forks of the motorcycle and on top of the motorcyclist's helmet. This configuration had a width of 1.33 ft (0.41 m) and a height of 5.11 ft (1.56 m). For the fully accentuated combined motorcycle headlight configuration, headlights were mounted on the handlebars, the forks, and on top of the motorcyclist's helmet to accentuate the full height and width of the motorcycle and its rider. This configuration had a width of 2.30 ft (0.70 m) and a height of 5.11 ft (1.56 m).

3.1.3 Displays

The lighting settings used to emulate nighttime driving were identical to Experiment 1. Almost all of the participants (*n* = 34) reported the roadway scenes accurately reflected the dark lighting conditions of nighttime driving on a rural highway with no streetlights. Identical to Experiment 1, participants were instructed to press a button on their keyboard as soon as they perceived the oncoming motorcycle was getting closer to them (i.e., when drivers first perceived closing).

3.2 Results

In line with Experiment 1, a 1.6 s PRT was subtracted from the time of the button press before calculating the optical expansion rate or the longitudinal bumper-to-bumper distance. If a participant responded less than 1.6 s into the roadway scene, that trial was removed from data analysis, and if a participant had one or more missing cells from too many trials with a response time of less than 1.6 s, then that participant was replaced. This resulted in four participants being replaced and 78 total trials (5.57%) from the remaining 35 participants being removed. The width of each oncoming vehicle's headlight configuration was used as the size in the optical expansion rate calculation, consistent with prior research (Muttart et al., 2005; Weaver et al., 2021). Based on whether any participants were more extreme than ±3 standard deviations from the mean, five participants were identified as outliers and replaced (the analyses for the current experiment did not change when outliers were not replaced). Shapiro-Wilk tests indicated the mean optical expansion rate significantly deviated from normally distributed for all of the headlight configurations except for the single motorcycle headlight configuration, but the sample size for the current experiment (n = 35) is large enough that this violation of the normality assumption is not of concern (Ghasemi & Zahediasl, 2012). Shapiro-Wilk tests indicated the mean longitudinal bumper-to-bumper distance did not significantly deviate from being normally distributed for any of the headlight configurations.

Results for mean optical expansion rate and mean longitudinal bumper-to-bumper distance were analyzed with a one-way repeated measures analysis of variance (ANOVA). A Greenhouse-Geisser correction was applied to the degrees of freedom when Mauchly's test was significant, which indicates a violation of the sphericity assumption. Significant effects were followed up with Holm-corrected repeated measures *t*-tests for all pairwise comparisons (Aickin

& Gensler, 1996; Holm, 1979; Levin, 1996). The effect size reported for an ANOVA is generalized eta squared ($\eta_G{}^2$; Bakeman, 2005; Olejnik & Algina, 2003).

A one-way repeated measures ANOVA on mean optical expansion rate showed that the effect of headlight configuration was significant, $F(4, 136) = 763.58$, $p < .001$, $\eta_G{}^2 = .839$. Holm-corrected repeated measures *t*-tests indicated all pairwise comparisons were significantly different as shown in Table 1. The headlight configuration with the smallest mean optical expansion rate was the motorcycle with the single headlight configuration ($M = 0.000083$, $SD = 0.000025$ rad/s) followed by the motorcycle with the fully accentuated vertical headlight configuration ($M = 0.000151$, $SD = 0.000059$ rad/s), the motorcycle with fully accentuated combined headlight configuration ($M = 0.000253$, $SD = 0.000062$ rad/s), the motorcycle with the tri-headlight configuration ($M = 0.000277$, $SD = 0.000082$ rad/s), and the car headlight configuration ($M = 0.000557$, $SD = 0.000107$ rad/s). These looming thresholds are ordered by the width of the headlight configuration such that larger widths had larger looming thresholds, which does not support Hypothesis 1. However, as I discuss later these results may be misleading because participants may have been making their judgments by incorporating other cues in addition to optical expansion rate.

A one-way repeated measures ANOVA on mean longitudinal bumper-to-bumper distance showed that the effect of headlight configuration was significant, $F(2.83, 96.31) = 39.16$, $p < .001$, $\eta_G{}^2 = .116$. As shown in Table 2, Holm-corrected repeated measures *t*-tests indicated all pairwise comparisons were significantly different except for between the motorcycle with the fully accentuated combined headlight configuration and the motorcycle with the fully accentuated vertical headlight configuration, and between the motorcycle with the single headlight configuration and the motorcycle with the tri-headlight configuration. Descriptively,

Table 1

Holm-Corrected Pairwise Comparisons of Headlight Configurations for Mean Optical Expansion Rate

Group 1	Group 2	t	df	Adjusted p	Cohen's d_z
Car	Single	32.2	34	< .001	5.44
Car	Tri-light	28.0	34	< .001	4.73
Car	Vertical	33.8	34	< .001	5.71
Car	Combined	29.2	34	< .001	4.93
Single	Tri-light	19.7	34	< .001	−3.32
Single	Vertical	10.3	34	< .001	−1.75
Single	Combined	24.4	34	< .001	−4.12
Tri-light	Vertical	19.1	34	< .001	3.23
Tri-light	Combined	4.32	34	< .001	0.73
Vertical	Combined	18.7	34	< .001	−3.16

Note. Car = Car Headlight Configuration; Combined = Motorcycle with Fully Accentuated Combined Headlight Configuration; Single = Motorcycle with Single Headlight Configuration; Tri-light = Motorcycle with Tri-Headlight Configuration; Vertical = Motorcycle with Fully Accentuated Vertical Headlight Configuration. Cohen's d_z was calculated based on the difference between the specified groups in which Group 2 was subtracted from Group 1; therefore, a positive Cohen's d_z means Group 1 has a larger optical expansion rate than Group 2, and a negative Cohen's d_z means Group 1 has a smaller optical expansion rate than Group 2.

the headlight configuration with the largest (larger is better) mean longitudinal bumper-to-bumper distance was the car headlight configuration (*M* = 687.69, *SD* = 58.32 ft; *M* = 209.61, *SD* = 17.78 m) followed by the motorcycle with the fully accentuated vertical headlight configuration (*M* = 644.40, *SD* = 79.76 ft; *M* = 196.41, *SD* = 24.31 m), the motorcycle with the fully accentuated combined headlight configuration (*M* = 642.82, *SD* = 70.86 ft; *M* = 195.93, *SD*

Table 2

Holm-Corrected Pairwise Comparisons of Headlight Configurations for Mean Longitudinal Bumper-to-Bumper Distance

Group 1	Group 2	t	df	Adjusted p	Cohen's d_z
Car	Single	8.64	34	< .001	1.46
Car	Tri-light	8.23	34	< .001	1.39
Car	Vertical	5.58	34	< .001	0.94
Car	Combined	7.07	34	< .001	1.20
Single	Tri-light	2.03	34	.102	−0.34
Single	Vertical	5.33	34	< .001	−0.90
Single	Combined	4.58	34	< .001	−0.77
Tri-light	Vertical	4.39	34	< .001	−0.74
Tri-light	Combined	4.36	34	< .001	−0.74
Vertical	Combined	0.28	34	.778	0.05

Note. Car = Car Headlight Configuration; Combined = Motorcycle with Fully Accentuated Combined Headlight Configuration; Single = Motorcycle with Single Headlight Configuration; Tri-light = Motorcycle with Tri-Headlight Configuration; Vertical = Motorcycle with Fully Accentuated Vertical Headlight Configuration. Cohen's d_z was calculated based on the difference between the specified groups in which Group 2 was subtracted from Group 1; therefore, a positive Cohen's d_z means Group 1 has a larger longitudinal bumper-to-bumper distance than Group 2 and a negative Cohen's d_z means Group 1 has a smaller longitudinal bumper-to-bumper distance than Group 2.

= 21.60 m), the motorcycle with the tri-headlight configuration (*M* = 619.60, *SD* = 82.00 ft; *M* = 188.85, *SD* = 24.99 m), and the motorcycle with the single headlight configuration (*M* = 608.95, *SD* = 85.75 ft; *M* = 185.61, *SD* = 26.14 m). Thus, participants perceived closing sooner for larger headlight configurations compared to smaller headlight configurations except for the smallest two headlight configurations. This means Hypothesis 2 was largely supported, but it may need a caveat, which is discussed later.

3.3 Discussion

The first hypothesis that drivers are more sensitive to larger headlight configurations compared to smaller headlight configurations was not supported because the headlight configurations with larger widths had larger mean optical expansion rates. Hence, these results appear to suggest drivers are more sensitive to smaller headlight configurations compared to larger headlight configurations. However, these results may be misleading because oncoming vehicles with smaller headlight configurations must be closer to the driver to reach a given rate of optical expansion, which coincides with other sensory cues being stronger, and drivers may incorporate other available sensory cues into their judgment. For example, drivers may incorporate the change in the brightness of an oncoming vehicle as the driver's vehicle's headlights illuminates it or the change in the rate of lateral movement across the driver's visual field. Because oncoming vehicles with smaller headlight configurations must be closer to the driver to reach a given rate of optical expansion, oncoming vehicles with smaller headlight configurations would be illuminated more by the driver's vehicle's headlights and moving laterally across a driver's visual field faster. This means oncoming vehicles with smaller headlight configurations would exhibit a smaller mean optical expansion rate not because drivers are more sensitive to smaller headlight configurations but rather because other sensory cues are stronger for smaller headlight configurations at a given rate of optical expansion, which drivers incorporate into their judgments. This explanation is supported by the longitudinal bumper-to-bumper distance results because they largely showed oncoming vehicles with smaller headlight configurations were closer to the driver before closing was perceived.

The second hypothesis that drivers perceive closing sooner for larger headlight configurations compared to smaller headlight configurations was largely supported. The results showed drivers perceived closing sooner for larger headlight configurations for all pairwise comparisons except for the pairwise comparison between the tri-headlight and the single headlight motorcycles. Thus, drivers perceived closing sooner for larger headlight configurations compared to smaller headlight configurations unless the headlight configurations were relatively small.

4. General Discussion

Broadly, the core objectives of the current research were to better understand how drivers perceive an approaching set of motorcycle headlights and to determine whether alternative motorcycle headlight configurations improved drivers' perceptual judgments of closing for an oncoming motorcycle. The results of Experiment 1 showed that the orientation of the headlight configuration did not affect the looming threshold for closing, which did not support the hypothesis that drivers would be more sensitive to horizontal optical expansion than vertical optical expansion. This finding provides contradicts Gould et al.'s (2012a) suggestion that drivers are more sensitive to looming along the horizontal axis compared to the vertical axis. Given Gould et al.'s (2012a) suggestion was based on a descriptive yet non-significant difference and the current work that conducted an a priori power analysis also did not find any significant difference, the available evidence suggests drivers are not more sensitive to optical expansion in one direction more than another. Theoretically, this finding means that drivers have not undergone perceptual learning for the task of judging closing on the roadway. This finding is consistent with theories based on optic flow, such as tau (Lee, 1976), which assume that sensitivity to optical expansion or tau is based on only the optical distance between two points and not the orientation of the two points.

The results of Experiment 1 also showed the looming threshold for closing for a combined horizontal-vertical headlight configuration was significantly smaller than a horizontal-only headlight configuration but not significantly different from a vertical-only headlight configuration. This finding does not support the hypothesis that drivers will achieve a lower looming threshold when both horizontal and vertical optical expansion is available. Theoretically, this means drivers are unable to integrate optical expansion from more than one dimension in a way that achieves a lower looming threshold and instead base their judgment on optical expansion from only one dimension, which in this case was the vertical dimension. This finding is inconsistent with the perceptual learning explanation that drivers base their perceptual judgments on looming in the horizontal direction more than the vertical direction.

This theoretical finding that drivers are unable to integrate optical expansion from more than one dimension is consistent with a strict interpretation of a looming detection threshold theoretical framework. This theoretical framework posits drivers perceive a given perceptual event on the roadway, such as closing, only when optical expansion rate exceeds a looming detection threshold. Hence, additional sensory cues, such as optical expansion along a second dimension, should not affect when a driver perceives a perceptual event on the roadway. A competing theoretical framework based on evidence accumulation could also account for these results, though it would need a caveat. The evidence accumulation theoretical framework posits that a driver makes perceptual judgments on the roadway once noisy sensory evidence has accumulated enough to reach a threshold (Markkula, 2014; Markkula et al., 2020). One key difference between this theoretical framework and the strict looming detection threshold theoretical framework is that this theoretical framework posits drivers may base their perceptual judgments on more than one sensory cue. Under the evidence accumulation theoretical framework, the current work suggests that optical expansion along only one dimension should be considered sensory evidence. Under both theoretical frameworks, the practical implication is that motorcycles only need headlights to accentuate the full extent of only one dimension. Given that the height of a motorcycle, including its rider, is longer than the width, the height should be accentuated with headlights.

Experiment 2 examined when, and at what looming threshold, drivers perceive closing for five different headlight configurations. The results of Experiment 2 showed the mean optical expansion rate was smaller for the headlight configurations with smaller widths, which does not support the hypothesis that drivers are more sensitive to larger headlight configurations. Although these results appear to suggest drivers are more sensitive to smaller headlight configurations, they may be misleading as we discussed previously because drivers may base their closing judgments on multiple available cues, which is consistent with the evidence accumulation model (Markkula, 2014; Markkula et al., 2020). In addition to the optical expansion rate of the oncoming vehicle's headlights, drivers may base their closing judgments on, for example, the change in the brightness of an oncoming vehicle as the driver's vehicle's headlights illuminates it or the change in the rate of lateral movement across the driver's visual field as the oncoming vehicle approaches in the adjacent lane. The results that showed drivers perceived closing sooner for larger headlight configurations (except for the smallest two headlight configurations) supported this explanation because it showed smaller headlight configurations were closer when drivers perceived closing. Under the evidence accumulation model, these additional sensory cues could be described as additional sensory evidence drivers used to make their perceptual judgments, which provides a parsimonious theoretical explanation for why drivers perceived closing at a smaller optical expansion rate for smaller headlight configurations. Future research could pit the evidence accumulation model against a strict looming detection threshold theoretical framework by manipulating the strength of different sensory cues drivers might use for closing judgments during nighttime driving.

The second hypothesis for Experiment 2 that drivers perceive closing sooner for larger headlight configurations was largely supported. The results of Experiment 2 showed drivers perceived closing sooner for larger headlight configurations for all pairwise comparisons except for the pairwise comparison between the tri-headlight and single headlight motorcycles. This may be because drivers primarily use other sensory cues (e.g., brightness of oncoming vehicle, lateral movement of oncoming vehicle) to judge closing for smaller headlight configurations because smaller headlight configurations do not reach an optical expansion rate drivers can detect before the accumulation of other sensory cues reaches a critical threshold. Thus, a revised hypothesis may posit that drivers perceive closing sooner for larger headlight configurations compared to smaller headlight configurations unless the headlight configurations are relatively small in which case drivers base their closing judgments primarily upon other sensory cues.

4.1 Practical Implications and Challenges

One of the objectives of Experiment 2 was to benchmark how good motorcycle headlight configurations that maximize its size are against a motorcycle with a "standard" single headlight, a motorcycle with a tri-headlight configuration, and a car's headlights. The results of Experiment 2 showed that motorcycle headlight configurations that accentuated the full extent of only a motorcycle's height or both a motorcycle's height and width were much better (all Cohen's $|d_z|$

> 0.74; perception of closing about 0.5 – 0.8 s sooner) than both a motorcycle with a single headlight and a motorcycle with a tri-headlight configuration. However, the motorcycle headlight configurations that accentuated the full extent of only a motorcycle's height or both a motorcycle's height and width were not nearly as good as (all Cohen's $|d_z| > 0.94$; perception of closing about 1 s later) the car's headlights. Thus, motorcycle headlight configurations that accentuated the full extent of only a motorcycle's height or both a motorcycle's height and width improved driver's perception of an approaching motorcycle relative to other motorcycle headlight configurations but not enough to make it comparable to a car.

Although there was no difference (no statistical difference and negligible effect size, $d_z = 0.05$) in when drivers perceived closing between the fully accentuated vertical motorcycle headlight configuration and the fully accentuated combined horizontal-vertical motorcycle headlight configuration, the fully accentuated vertical motorcycle headlight configuration may be better in terms of practicality because it requires fewer headlights and therefore costs less. For either configuration, motorcyclists would need to wear a helmet-mounted headlight, which is not a very common practice on the roadway today. Buy-in from motorcyclists would be needed. Future research could examine motorcyclists' attitudes towards wearing a helmet with a headlight to improve other driver's perception of them. Some previous road safety measures, such as seat belts, were initially met with high resistance (Lasalandra, 1986; Wolinsky, 1985), though became increasingly accepted and used (Hedlund et al., 2008; National Center for Statistics and Analysis, 2019). Helmet-mounted headlights could meet this same resistance. Moreover, motorcyclists turning their head would change how the oncoming motorcycle appears to a driver. Future research could examine how this affects driver's perceptions.

4.2 Low Looming Thresholds

The looming thresholds observed in the current research (Experiment 1: $M = 0.000279$ rad/s; Experiment 2: $M = 0.000264$ rad/s) were much lower compared to the looming threshold for closing typically observed in prior research of about 0.003 rad/s (Hoffmann & Mortimer, 1994, 1996; Mortimer et al., 2014; Weaver et al., 2021). Gould et al. (2013) also found notably smaller looming thresholds for closing of about 0.000873 rad/s. One characteristic of the driving scenarios unique to the current research and Gould et al. (2013) is that participants were judging when they perceived closing for an oncoming vehicle. However, the majority of research on the looming threshold for closing has had participants judge when they perceived closing for a lead vehicle traveling in the same direction (Hoffmann & Mortimer, 1994, 1996; Mortimer et al., 2014; Weaver et al., 2021). Hence, drivers may perceive closing at a lower optical expansion rate when judging an oncoming vehicle compared to a lead vehicle. This could be because drivers have a lower evidence accumulation threshold for oncoming vehicles, which could be because there may be more uncertainty for lead vehicles. For example, lead vehicles could be getting farther away, maintaining the same distance, or getting closer, but oncoming vehicles are typically getting closer because they are travelling in the opposite direction. There may also be additional sensory cues that indicate closing for oncoming vehicles, which are not present for lead vehicles. For instance, oncoming vehicles in the adjacent lane have some lateral movement across the driver's visual field when they approach, which is not present for lead vehicles in the same lane.

Given the thresholds in the current research are low even compared to Gould et al. (2013), the factors discussed so far may only partially account for why the looming thresholds in the current research were low. One key difference between the current research and Gould et al.

(2013) was time of day. The current research had nighttime driving conditions, whereas Gould et al. (2013) had daytime driving conditions. Nighttime driving scenarios may make it easier for drivers to perceive closing because there is less visual clutter, which makes the oncoming vehicle more salient compared to daytime driving. Future research could further examine whether these factors account for the difference in observed looming thresholds.

4.3 Limitations and Future Research

One limitation of the current research is that the driving simulator and remote nature of the experiments may not have been a perfect emulation of the dark lighting conditions of nighttime driving. For example, participants may not have experienced glare from the oncoming vehicle's headlights because their screen was not able to reproduce such strong light intensity in a localized area. Even so, nearly all of the participants (67 out of 70) in the current research reported the roadway scenes accurately reflected the dark lighting conditions of nighttime driving on a rural highway with no streetlights. Future research could examine whether the observed effects of headlight configuration change when studied on an actual roadway. Another limitation is the method of working backward from a button press using an assumed perception-response time to infer when perception took place. For example, it is possible perception-response time is different for different driving conditions (e.g., daytime versus nighttime driving). Future research should examine what factors affect perception-response time for use by researchers and accident analysts.

4.4 Conclusion

The results of the current research showed drivers did not perceive closing at different looming thresholds for different headlight orientations, which is inconsistent with a perceptual learning framework that posits drivers become more sensitive to horizontal expansion. The results also showed drivers could not achieve a lower looming threshold when both horizontal and vertical optical expansion was provided, meaning drivers are unable to integrate optical expansion from more than one dimension in a way that achieves a lower looming threshold. This means that in terms of drivers' perceptual judgments of closing, a headlight configuration that accentuates the full height of a motorcycle and its rider (its longer dimension) might be the best motorcycle headlight configuration. This was shown to be true in the second experiment, but it was still not as good as a car. Theoretically, the current research favors an evidence accumulation model because it can give a more parsimonious account for why drivers perceived closing at a smaller mean optical expansion rate for smaller headlight configurations and for why the current research had lower looming thresholds compared to prior research. Future research should aim to further develop the evidence accumulation model as it may better reflect how drivers make perceptual judgments and subsequent driving actions on the roadway.

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