Judgments of approach speed for motorcycles across different lighting levels and the effect of an improved tri-headlight configuration

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Abstract

The misperception of vehicle approach speed is a key contributory factor to road traffic crash involvement. Past research has indicated that individuals use the rate of visual looming to calculate the time to passage (TTP) of a vehicle, and that smaller vehicles loom to a lesser extent than larger vehicles. Despite a disproportionate number of fatal injuries occurring on the road after dark, and a higher than average number of accidents involving automobile drivers violating the right of way of a motorcyclist occurring in low light conditions, there has been very little consideration of the accuracy of TTP for smaller and larger vehicles under low levels of luminance. We investigated drivers’ judgments of motorcycle and car approach speeds across a number of levels of luminance within a virtual city scene, as well as the effectiveness of a tri-headlight formation on motorcycle speed judgments. The accuracy of car approach speed judgments were not affected by changes in lighting conditions, but speed judgments for the solo headlight motorcycle became significantly less accurate as lighting reduced in the early night and nighttime conditions. Incorporation of a tri-headlight formation onto the standard motorcycle frame resulted in improved accuracy of approach speed judgments, relative to the solo headlight motorcycle, as ambient light levels reduced. The practical implications of the findings are discussed in terms of road safety and motorcycle design.

1. Introduction

The misperception of vehicle approach speed is a key contributory factor to road traffic crash involvement (Hurt et al., 1981; Pai et al., 2009; Peek-Asa and Kraus, 1996; Brenac et al., 2006; Department for Transport, 2010a). For example, the risk of collision is increased if an observer underestimates the distance and speed of an oncoming vehicle, as the vehicle will be perceived as reaching them later than it actually would, thus leaving less time available to perform a manoeuvre such as pulling out from a junction. Furthermore, perceptual limitations in judgments of vehicle approach may be compounded in lower light conditions. Indeed, a disproportionate number of fatal injuries occur on the roads after dark (Pai et al., 2009; Plainis et al., 2006). According to the Community database on Accidents on the Roads in Europe (CARE), while the number of drivers on the road during low level lighting conditions is far fewer than during daylight hours, statistics indicate that approximately 50% of all fatal accidents occur between the hours of 6 pm and 6 am (ERSO, 2008).

Research has provided a substantial amount of evidence to suggest that drivers are less
capable of avoiding collisions under reduced lighting conditions compared with daylight conditions, and accidents involving pedestrians (Sullivan and Flannagan, 2002) and rear-end collisions with other motor vehicles (Sullivan and Flannagan, 2003) are particularly prevalent. Consequently, there is little disagreement that driver vision in the dark is seriously impaired when compared with daylight conditions (Sullivan et al., 2004). Very little research, however, has focussed on the perception of vehicle approach under low light conditions.

Gauging the time-to-passage (TTP) of an oncoming vehicle has traditionally been expressed as a ratio of the vehicle’s distance ($z$) and speed of approach ($v$) for a given period of time ($t$). However, estimating metric properties such as relative distance is problematic as judgments can be biased by other cues such as the vehicle’s height in the scene (see Wann et al., 2011 for further discussion). A more reliable indicator of relative distance and speed is the vehicle’s optical size vehicle’s optical size $\theta(t)$ divided by its rate of expansion $\dot{\theta}(t)$ (Lee, 1976):

$$\text{TTP} = \frac{z(t)}{v(t)} = \frac{\theta(t)}{\dot{\theta}(t)}$$

As discussed in Gould et al. (2012), a problem can arise with Eq. (1) due to the fact that the rate of expansion is dependent on the size of the vehicle ($S$), which could be taken as either the width, height or combined surface area:

$$\dot{\theta}(t) = \frac{Sv(t)}{z^2(t)}$$

When applied to a driving scenario, Eq. (2) demonstrates that when travelling at the same speed, a larger vehicle will loom to a greater extent than a smaller vehicle. This raises the possibility that for two different sized vehicles at the same distance from the observer, and travelling at the same speed, the smaller one will appear to be travelling slower and thus will be perceived as reaching the observation point at a later time than the larger vehicle. Under optimal lighting conditions, an effect of vehicle size is noticed in terms of drivers’ ability to judge speed accurately (Caird and Hancock, 1994; Horswill et al., 2005). More specifically, individuals may be less accurate when judging the speed of smaller vehicles, such as motorcycles, compared with larger vehicles, as a consequence of their smaller frontal surface area (Pai, 2011). This may explain in part why motorcycles are overrepresented in crashes when a driver commits a right of way violation by pulling into the path of an oncoming motorcyclist (Pai et al., 2009; Peek-Asa and Kraus, 1996). This problem will be exacerbated for motorcyclists when night falls, as the contours of the rider and vehicle can no longer be depicted. Therefore only the diameter of the solo head-light can be used to determine TTP, yielding less accurate judgments of approach speed (Gould et al., 2012). Research on gauging vehicle approach, however, has typically been conducted under optimal lighting conditions, with little consideration of how the accuracy of TTP estimates may be affected under lower luminance levels.

In terms of the effect of lighting conditions on motion processing, past research has demonstrated that the processing of visual information under low luminance and contrast is much poorer than for brighter objects and that furthermore, individuals are extremely poor at judging the speed of objects under low lighting conditions (Gergenfurtner et al., 1999; Plainis et al., 2006). Researchers have provided evidence that this is primarily due to the reliance of the
visual system on information provided by rod photoreceptors during low light level conditions, opposed to the cone photoreceptors that are used during higher lighting levels. More specifically, motion perception using rods is seriously impaired, while spatial and temporal resolution also suffer (Hess et al., 1990; Gergenfurtner et al., 1999).

Given the evidence that human processing of visual motion is degraded when luminance levels are reduced under strict psychophysical conditions, it is possible that judgments of approach speed are also affected in lower light conditions (Pai et al., 2009). Over the course of the year in the UK, motorcycle traffic volume is at its highest between the hours of 7–9 am and 3–7 pm, with the peak travel time evident between 4 and 6 pm (Department for Transport, 2010b). While research has suggested that road accidents are less prevalent during the longer hours of the summer months (Sullivan and Flannagan, 2002), in mid-December the sun does not rise until 8 am and sets before 4 pm, thus creating a situation where motorcycles are likely to be travelling during dim light conditions. More specifically, in a mixed logit analysis of UK police reports on traffic collisions (Stats19), Pai et al. (2009) demonstrated that a higher than average number of accidents involving automobile drivers violating the right of way of a motorcyclist occurred during dusk street lighting periods, in the evening and midnight/early morning periods of the day and during the autumn/winter months.

One potential countermeasure to improve sensitivity to motor-cycle approach is the addition of extra motorcycle headlights. Previous research has demonstrated that a greater separation distance between headlights can lead to improved distance judgments when speed remains constant (Castro et al., 2005). Furthermore, the introduction of a tri-headlight formation on a standard motorcycle frame, where the distance between the lights increases on both the horizontal and vertical axes during visual looming, can greatly improve speed judgments for motorcycles (Gould et al., 2012). In the latter study, headlights were presented as approaching the observer on a black background, with absolutely no vehicle contour visible. The control condition featured a daylight condition, where the photographic vehicle stimulus approached the observer viewpoint on a mosaic tarmac background. In addition to making the visible profile larger, this condition included cues such as relative size and occlusion which can affect arrival judgments (DeLucia et al., 2003).

Ambient light levels, however, do not change from broad daylight to absolute night in one step, so in this study we looked at judgments of approach speed in a con-textual virtual road scene, and investigated how judgments were affected as simulated lighting levels fell.

The aim of the present study was to determine the extent to which sensitivity to approach speed declines as luminance levels decrease and how judgments for motorcycles and cars might be differentially affected. We utilised computer simulations of photographic images of a car, a solo headlight motorcycle, and a tri-headlight motorcycle approaching the observer viewpoint in a virtual city environment. These simulations took place across five different simulated ambient light level conditions, ranging from levels approximating broad daylight to night-time conditions. We predicted that the accuracy of speed judgments for the car would be least affected across the reduced lighting conditions, but that the accuracy of judgments for the solo headlight motorcycle would decrease as the simulated light level was reduced. We predicted that the motorcycle fitted with the tri-headlight
formation would improve the accuracy of speed judgments for the motorcycle across all lighting conditions.

2. Method

2.1. Participants

A sample of 14 participants, 8 male and 6 female, were recruited from Royal Holloway, University of London. The participants ranged from 22 to 49 years of age, with average age of 32 years (SD 8.93 years). All participants were required to have possessed a valid United Kingdom driving licence for at least one year and were requested to wear their usual corrective eyewear during the experiment. The study was approved by the Department of Psychology ethics panel.

2.2. Apparatus

The experiment utilised a 34 cm × 27 cm cathode ray tube monitor display, with an aspect ratio of 1.26 and resolution of 1024 × 768. The simulations were scripted in Python and used Vizard 3D simulation tools (WorldViz, USA). The Vizard libraries sit on top of OpenSceneGraph and provide the ability to render highly realistic 3D simulations that are perspective correct and run at the maximum screen refresh rate (60 Hz). The rendering hardware was an Intel® dual core CPU with an NVidia high performance GPU running under Windows XP. The simulation code used a 60 Hz timer-loop, which ensured that the correct vehicle size and rate of expansion was presented for every frame of each trial. The reference ambient light levels that formed a basis for the simulated luminance in the experimental scenes were recorded using a Minolta photometer.

2.3. Experimental conditions and design

The methodology utilised in this experiment was a discrimination paradigm (see Gould et al., 2012), whereby participants were asked to indicate which of the two visual stimuli was travelling at the greater speed. This methodology has been utilised in various past psychophysical research studies in order to investigate perceptual threshold judgments (e.g., Beardsley and Vaina, 2001; Field and Wann, 2005; Todd, 1981). Each trial featured a photographic car stimulus that acted as a reference vehicle that always travelled towards the observation point at 30 mph (13.4 ms). A probe vehicle (car, solo headlight motorcycle or tri-headlight motorcycle) approached at a range of speeds and the order of presentation of the reference and probe vehicle was randomized. The motorcycle headlight and the car headlights were 20 cm in diameter, while the car headlights were separated by a distance of 160 cm. The tri-headlight configuration consisted of a main headlight diameter of 20 cm, with two additional 10 cm diameter flanking lights placed 30 cm below and to the right and left of the main headlight. All distances between headlights were measured from the centre point of each headlight. The speed differences between the probe and reference vehicles ranged from −20 mph to +180 mph. The probe vehicle was manipulated using a parameter estimation by sequential testing procedure (Best-PEST; Lieberman and Pentland, 1982). This procedure calculates the optical increment in speed for each trial based on the participant’s previous responses to efficiently converge on their threshold performance. The PEST staircases were stopped after the seventh reversal. Participant judgments of the speed.
difference between the probe and the reference vehicle were recorded for each trial and the threshold for speed discrimination was calculated as the average of the speed differences for the last four reversals.

2.4. Levels of ambient lighting

The vehicle stimuli were presented in a virtual urban city environment and travelled along the road surface towards the observation point. The ambient light levels were adjusted within the virtual scene to simulate five different daylight conditions (daylight, lower daylight, dusk, early evening and night). It is not possible to set these to absolute levels as the maximum level of illumination provided by a CRT on full brightness with a white screen is $\sim 95$ cd/m$^2$ whereas a sunny day in the UK exceeds 725 cd/m$^2$. But that difference is not perceived by a human observer because we perceive relative light levels and an observer may often feel that a computer screen is “too bright” even when its ambient level is well below that of a “grey day”. We therefore took ambience readings using a photometer at five different times of day. These readings were then converted to provide an index of the percent-age decrease in lighting levels over the course of five time periods, resulting in the settings for five levels of ambient light within the virtual scene (see Table 1 for values and Fig. 1 for visual illustration of the lighting conditions). All areas of the virtual scene and the stimuli were programmed to react to the ambient lighting level. The virtual scene did not feature any street lights as the primary focus of the study was to investigate object expansion under differing luminance levels.

2.5. Procedure

Participants sat 1 m from the computer monitor, with an eye height of 1.2 m and viewed all of the presentations binocularly. Participants were then given a small number of practice trials prior to each condition so that their understanding of the procedure could be verified. The participants were asked to click an “OK” button in order to start the series of trials and asked to indicate which of the two sequentially presented stimuli was travelling fastest by click-ing on a button with the number “1” or a button with the number “2” in order to select the first or second vehicle respectively. The stimuli were displayed for 500 ms each with an inter-stimulus gap of 750 ms. The order in which the probe and reference stimuli were presented was randomised. All stimuli had a time to passage of four seconds. The experimental design utilized was repeated measures with the order of conditions randomised for each participant.
Table 1

Luminance readings for real scene settings taken at different times of day in the UK during winter and equivalent % decrement settings for virtual scene to provide simulations of different daytime conditions.

<table>
<thead>
<tr>
<th>Real Scene Luminance Reading cd/m²</th>
<th>% of max</th>
<th>Time</th>
<th>Virtual Scene Luminance Reading cd/m²</th>
<th>% of max</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>687.65</td>
<td>100</td>
<td>1200</td>
<td>8252</td>
<td>100</td>
<td>Daylight</td>
</tr>
<tr>
<td>194.06</td>
<td>28.22</td>
<td>1412</td>
<td>32.74</td>
<td>26.60</td>
<td>Lower Daylight</td>
</tr>
<tr>
<td>21.31</td>
<td>3.10</td>
<td>1635</td>
<td>7.1</td>
<td>2.29</td>
<td>Dusk</td>
</tr>
<tr>
<td>3.92</td>
<td>0.57</td>
<td>1703</td>
<td>1.94</td>
<td>0.14</td>
<td>Early Night</td>
</tr>
<tr>
<td>0.86</td>
<td>0.13</td>
<td>1726</td>
<td>1.01</td>
<td>0.019</td>
<td>Night</td>
</tr>
</tbody>
</table>

Figure 1

Three screenshots of the virtual lighting levels used for daylight, dusk, and early night-time.

3. Results

A two-way repeated measures ANOVA was conducted with 5 levels of lighting (daylight, lower daylight, dusk, early night, night) and the 3 vehicle types (car, solo headlight motorcycle, tri-headlight motorcycle) on participant threshold judgments for speed discrimination. This revealed a significant main effect of light level ($F(4, 52) = 3.979, p < .01, n_2p = .234$) and a significant main effect of vehicle type ($F(2, 26) = 21.286, p < .001, n_2p = .621$). The ANOVA also revealed a significant interaction between light level and vehicle type ($F(8, 104) = 4.550, p < .01, n_2p = .259$). A follow-up one-way repeated measures ANOVA for the car stimulus alone did not reveal a significant main effect for light level ($F(4, 52) = .489, p > .05, n_2p = .036$). Conversely, a one-way repeated measures ANOVA for the solo headlight motorcycle stimulus revealed a significant main effect for light level ($F(4, 52) = 5.575, p < .005, n_2p = .300$). Planned pairwise comparisons revealed that participants were significantly more accurate at judging the speed of the solo headlight motorcycle in the daylight condition compared with the early night ($p < .05$, 95% CI: $-33.537$ to $-2.825$) and the night conditions ($p < .01$, 95% CI = $-58.283$ to $-11.587$). The participants were also significantly more accurate at judging the speed of the solo headlight motorcycle in the lower daylight condition compared with the night condition ($p < .05$, 95% CI: $-55.555$ to $-7.327$) and in the dusk condition compared...
with both the early night (p < .05, 95% CI: −29.535 to −.589) and night (p < .05, 95% CI: −55.129 to −8.503) conditions. Finally, a one-way repeated measures ANOVA for tri-headlight motorcycle found no significant differences in the accuracy of speed judgments across the different light conditions (F(4, 52) = 1.215, p > .05, n²p = .086). The data is illustrated in Fig. 2. In order to compare the differences in thresholds between vehicles in each lighting condition, a priori independent t-tests were run. The tri-headlight motorcycle yielded more accurate judgments than the solo headlight motorcycle in the early night condition (t(13) = 4.619, p < .01, 95% CI: 12.511–34.495) and in the night condition (t(13) = 3.585, p < .05, 95% CI: 16.236–65.487). The car stimulus yielded more accurate judgments than the tri-headlight motorcycle in the daylight condition (t(13) = −2.400, p < .05, 95% CI: −12.540 to −6.60), lower daylight (t(13) = −2.839, p < .05, 95% CI: −15.913 to −2.161) and the night condition (t(13) = −2.830, p < .05, 95% CI: −12.855 to −1.725).

**Figure 2**

Participant judgments for vehicles across ambient light level conditions where the speed difference (mph) between the reference car and the probe vehicle was manipulated.
4. Discussion

The present study examined how accurately individuals are able to judge the speed of motorcycles and cars across a number of different ambient light level conditions. The results demonstrate that the accuracy of individuals' judgments remained constant across all lighting levels for the car stimulus, presumably because observers are utilising the rate of separation of vehicle headlights as a cue for time to passage in night-time driving conditions (Castro et al., 2005; Gould et al., 2012). The results show that participant estimations of the solo headlight motorcycle speed became significantly less accurate in the degraded lighting levels of the early night and night-time conditions. This is presumably because unlike a car the visible extent of a motorcycle changes dramatically as the light level falls. The decrement appeared to be most dramatic just after our simulation of dusk conditions (Fig. 2). The finding that participants were significantly more accurate at judging the speed of the car compared with the solo headlight motorcycle across all conditions provides support for previous assertions that there is a linear relationship in speed judgments across vehicle size (Caird and Hancock, 1994; Horswill et al., 2005). The potential impact of the effect is that observers' judgments for the solo headlight motorcycle declined from a 21 mph speed difference in the day-light condition, to a 39 mph and 56 mph speed difference in the early night and night-time conditions respectively. This means that a motorcycle travelling at over 70 mph at night-time would be perceived as travelling at the same speed as a car travelling at 30 mph. If a driver was looking for a time gap of approximately four seconds to execute a pull out manoeuvre from a junction, the errors observed for judging the approach rate of motorcycles in evening/night-time conditions would have reduced that time to below two seconds.

Without increasing the physical size of the motorcycle so that the frontal surface area and headlight distance are equivalent to that of a car, this trend is unlikely to change. Increasing motorcycle headlight separation is one way of maintaining the visible width of the vehicle as night falls, and the addition of the tri-headlight formation considerably reduced the degradation in speed judgments under lower light conditions in this experiment. There appears to be some variability in judgments for the tri-headlight at Dusk (see Fig. 2), but this may be artifactual. The return to daylight performance during night-time conditions confirms the efficacy of the tri-light and demonstrates that the effect demonstrated by Gould et al. (2012) holds for contextual scenes with realistic lighting levels.

We acknowledge, however, that the introduction of the tri-headlight configuration does not eradicate perception errors. Judgments were still poorer than those for the car, and the errors for the tri-headlight would still have reduced the pull-out time available to a driver from four seconds down to approximately three seconds. So while this is less than is optimal the introduction of the tri-headlight formation could prove decisive in whether a motorcycle collision is narrowly avoided or a right of way violation collision takes place. The difference between the car and motorcycle is in line with the separation that is possible for the headlights. If the tri-headlights could be spaced 1.6 m apart we would predict that the relative difference would disappear all together, but that would render a motorcycle as far less useful as a small manoeuvrable vehicle. An alternative would be to space the lights vertically (e.g. using the lower parts of the bike and the riders helmet), but in this study we were focusing upon a solution that could be
engineered into a motorcycle, or be a structured addition to existing bikes. This does not exclude other means of increasing the conspicuity of the rider, such as reflective vests. But for the conditions and scenario we have considered reflective clothing will only be illuminated when car headlights shine directly upon them. This will not occur when cars are waiting to pull out from junctions, which is a manoeuvre that is particularly associated with right of way violations when the approaching vehicle is a motorcycle. The research on the efficacy of enhanced rider conspicuity is inconclusive (Hole et al., 1996; Pai, 2011) and part of this may be due to the illumination that is directed towards a reflective vest when the observer is waiting at a transverse junction. In our previous study (Gould et al., 2012) we discussed the trade-off that is evident in the area of driving research between the ecological validity of applied research and the control that can be achieved within a laboratory setting. In this study, while we selected a methodology that measured drivers’ abilities to discriminate between the speeds of three different vehicles, we assessed this within a contextually rich virtual scene. This allowed us the ability to exercise strict control and calculate thresholds for speed discrimination, while also including additional cues such as relative height in the scene and occlusion that would be present in a real world scene. It remains the case, however, that our data was not collected on the road using real vehicles, although it is difficult to see how a methodology with equivalent experimental control could be translated to the road. What we demonstrate here is that some of the essential perceptual judgments, that would be required at the roadside, are impaired when presented with a single headlight vehicle under poor lighting conditions. These errors maybe even greater in a natural road scene where there are other distracters; it is unlikely that they would improve when there is much more visual noise in the scene. UK Road traffic casualty statistics show that motorcyclists are more likely to be killed or seriously injured on the road than any other road user (Department for Transport, 2010a). Furthermore, research has demonstrated that the motorcycle-automobile accident involvement at night is higher relative to daylight hours (Pai et al., 2009) and that motorcycle conspicuity is inadequate in dark and low light conditions (Williams and Hoffman, 1979). The issue of how to reduce motorcyclists’ vulnerability under sub-optimal luminance levels is not straightforward, but our study has provided evidence that the inclusion of the tri-headlight configuration is an engineering intervention with potential for reducing the level of misperception that occurs when considering motorcycle approach speed. Recent UK media campaigns have attempted to increase driver awareness that motorcycles may not be noticed when drivers scan a road scene. In addition to that, our studies suggest that even if they notice a motorcycle in the scene, drivers might not be accurate in their judgment of the speed at which it is traveling. It would therefore be beneficial for future safety campaigns to also aim to increase driver knowledge of the potential for inaccurate judgments of vehicle approach, particularly for motorcycles, and stress that under low luminance conditions, these errors may increase significantly. On a closing note we would suggest that our findings with single headlight motorcycles also probably apply to cars where there is only one clear headlight. When a bulb blows in a car headlight there is normally still a sidelight illuminated this is much lower intensity and has poor visibility at ∼50 m. Most drivers are unaware that continuing to drive with only one headlight may lead other drivers to grossly mis-perceive their approach speed and lead to other drivers pulling across their path. If confirmed
this is an issue that could be addressed through public information on night time driving.

References


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