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Drives' gap acceptance and time to arrival judgements when confronted with approaching bicycles, e-bikes and scooters

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Abstract

Previous studies have shown that time to arrival estimates (TTA) as well as accepted gap size are influenced by vehicle size. Drivers tend to choose smaller gaps and provide longer TTA estimates when confronted with smaller vehicles compared to larger ones. Object size alone, as well as the potential threat ascribed to the approaching vehicle have been suggested as being the factors that underlie this bias. To assess the merit of these potential explanations, we used different types of two-wheelers (bicycle, e-bike, scooter) of roughly the same size, but substantial differences in the potential threat they pose. Participants saw videos of approaching two-wheelers, and were required to either indicate the smallest acceptable gap, or to estimate TTA (2 blocks). Participants accepted smaller gaps for the two bicycle types than for the scooter. Likewise, TTA estimates for the two bicycles were longer than for the scooter. These results indicate that certain characteristics of the vehicle unrelated to physical size, such as the potential threat the vehicle poses, play a role in the assessment of a vehicle's approach. This implies that other road users might select potentially risky gaps when turning in front of bicycles and e-bikes in traffic.

Keywords*:* gap acceptances, time-to-arrival, size arrival effect, time-to-collision

1. Introduction

Observations of road user interactions at intersections have shown that drivers of motorised vehicles tend to choose smaller gaps for crossing / turning in front of smaller vehicles, e.g. motorcycles, as compared to cars (Hancock, Caird, Shekhar, & Vercruyssen, 1991; Keskinen, Hiro, & Katila, 1998; Pai, 2011). This finding suggests that there might be an increased crash risk for two-wheelers in such situations, an assumption that is indeed reflected in accident statistics. Such statistics show that intersections, or, more broadly, situations in which other road users cross the path of a cyclist or a motorcyclist are major risk factors (Haworth & Debnath, 2013; OECD/International Transport Forum, 2012). A comparative assessment of motorcycle and bicycle crash data showed that for both vehicle types, most crashes occurred at intersections, and the other conflict partner (usually a car driver) was at fault in most cases (Haworth & Debnath, 2013). It appears that, for different reason, the drivers' decision making process with regard to crossing or turning in front of approaching two-wheelers is impaired.

One potential explanation that has been discussed is the fact that the size of objects (measured as the visual angle they cover on the observers' retina) influences the perception of their approach. Several studies have investigated the so called time to arrival (TTA, often also time to collision, TTC), which is defined as "the time remaining before something reaches a person or particular place" (Tresilian, 1995, p. 231). Such investigations usually have been able to show that smaller vehicles appear to arrive later than larger vehicles at an observation point. Horswill et al. (2005), e.g., confronted their participants with short video sequences depicting the approach of a motorcycle, a car, and a van, and found that TTA estimates for motorcycle approaches were longer compared to the two larger vehicles (Horswill, Helman, Ardiles, &

Wann, 2005). The authors concluded that this "illusion" has the potential to directly increase the risk of crashes at intersections.

Others have argued that main reason for the effect of vehicle size on drivers' decisions is the potential threat ascribed to the approaching vehicle. Caird and Hancock (1994) argued that TTA estimates are biased as a result of the margins-of-safety hypothesis, which stated "that larger vehicles are given more space-time" (Caird & Hancock, 1994, p. 97). Following this line of thought, Das et al. (2005) argued that drivers might include the expected costs of a crash in their decision, which means that it would make a difference "whether the oncoming vehicle is a rickshaw or a bus" (Das, Manski, & Manuszak, 2005, p. 17).

To assess the merit of these potential explanations, size and threat of the approaching objects need to be disconnected, e.g. by using vehicles that are similar in size, but differ in the potential threat they pose to the driver of a car. Different types of two-wheelers, e.g. bicycles and motorcycles, might allow for the required discrimination, as they have roughly the same size (with regard to visual angle), but differ substantially in perceived threat. Hydén, Nilsson and Risser (1999) argued that cyclists are hardly threatening to car drivers, which results in drivers paying more attention to other road users who could harm them (Sissons Joshi, Senior, & Smith, 2001), and neglecting forms of behaviour that might prevent crashes with bicycles (Oxley, Corben, Fildes, O'Hare, & Rothengatter, 2004). In contrast, motorcyclists are often characterised as speeders or "foolhardy riders" (Ragot-Court, Mundutéguy, & Fournier, 2012, p. 97), which certainly might lead to the perception that their behaviour is more dangerous than the cyclists'. The higher weight of a motorcycle compared to a bicycle, which would mean a higher crash severity in case a crash occurred, might increase the level of perceived threat even further. Therefore, it appears that an experimental comparison of bicycles and motorcycles with regard to perceived TTA and accepted gap size could shed some light on the question of whether potential threat can serve as an explanation for differences in these variables between different types of vehicles.

It has to be acknowledged, however, that there are a number of additional aspects that are known to influence TTA estimates and gap acceptance. One of the most stable effects is the influence of speed, with higher speed levels resulting in longer TTA estimates than lower speeds (Petzoldt, 2014; Recarte, Conchillo, & Nunes, 2005; Sidaway, Fairweather, Sekiya, & McNitt-Gray, 1996). Cooper, Storr and Wennell (1977) were able to observe a corresponding effect for gap acceptance in real traffic, with the mean accepted gap size decreased by about 1.5 s when the speed increased by 20 mph (32 km/h). This effect was also confirmed in a number of driving simulator studies (Bottom & Ashworth, 1978; Hancock et al., 1991; Yan, Radwan, & Guo, 2007).

It should be noted that also the type of the bicycle might impact on drivers' decision making. In a test track study, Petzoldt, Schleinitz, Krems and Gehlert (2017) found drivers tended to indicate shorter acceptable gaps for crossing in front of an electrical bicycle, as compared to a conventional one. As an explanation it was suggested that the drivers' perception of the riders' effort, as apparent in their pedalling frequency and body posture, might have influenced the drivers' impression of the riders' approach speed.

The age of the observer seems to play a role as well (Hancock & Manser, 1997; Schiff, Oldak, & Shah, 1992). Older observers usually show a significantly impaired accuracy in TTA estimations compared to younger ones. They provide consistently shorter estimates than younger observers, i.e., older drivers perceive vehicles as arriving much earlier and tend to accept larger gaps than younger ones (Alexander, Barham, & Black, 2002; Keskinen et al., 1998; Yan et al., 2007).

The primary aim of the experiment presented in this paper was to investigate the effect of the type of two-wheeler (motorcycle, e-bike, bicycle) on drivers' TTA estimates and gap acceptance. As additional factors, the speed of the two-wheelers and the observers' age were included in the experimental design to account for potential interaction effects between these variables and the investigated vehicle types with regard to TTA estimates and accepted gap size.

2. Method

2.1 Participants

Forty-four participants in two age groups (30-45 years, 65 years and older) took part in the experiment. Table 1 provides an overview of age and gender of the participants. All of them had a drivers' license, were active drivers and had normal or corrected visual acuity. For their participation, they received monetary compensation.

[Insert Table 1 here]

2.2 Experimental design

We conducted a video-based laboratory experiment with scenes of different two-wheelers approaching an observer. The experiment included a TTA estimation block and a gap acceptance block, both of which made use of the same basic video material. The videos showed three different two-wheelers: a conventional trekking bicycle (Diamant Ubari black), a comparable e-bike (Diamant Supreme) and a scooter (Motowell Crogen RS 95, motorcycle). All two-wheelers approached at constant speeds of either 25, 30 or 35 km/h. The age group of the participants served as between factor (see Table 2). In the TTA estimation block, in addition to two-wheeler type and speed, three different TTAs were used to avoid potential learning effects that might allow the participants to use other strategies (such as distance at end of video) to infer TTA. This resulted in 27 within-factor level combinations for this block, in which participants' TTA estimates were measured as dependent variable. In the gap acceptance block, the size of the gap which was chosen by the participants was measured for a total of 9 within-factor level combinations.

[Insert Table 2 here]

2.3 Material

Video material was recorded on a straight taxiway of a small general aviation airport. The videos showed a driver's point of view, i.e. the height of the camera position was comparable to the eye level of a driver sitting in a car (see Figure 1). A white line was pasted across the road surface to mark the position of a potential collision between the approaching two-wheeler and the observer's vehicle when turning left. As the airport was rather deprived of depth cues, two black cars were put into the scenery as anchors, so it would be easier for the participants to familiarize themselves with the bicycle's size and approach in the trials of the experiment. All combinations of two-wheeler type and speed were filmed. The riders of the two-wheelers were free to choose an appropriate gear to reach each speed level. The e-bike rider was instructed to use a level of motor assistance that appeared suitable for him.

For the TTA estimation block, the videos were shortened to a length of 4 s, and cut in a way so that at the end of the clip, the approaching vehicle had a TTA according to one of the three defined levels (i.e., 4, 6 or 8 s away from arriving at the white line). In the gap acceptance block, videos were cut so that the approaching two-wheeler was always in a distance of 100 m from the white line at the start of the clip, and continued until the vehicle had passed the position of the observer (resulting in variable clip length, dependent on approach speed).

The video material was presented using a projector. Participants were seated at a desk in a distance of 2.50 m from the projection (1.25 x 2.20 m). The resulting visual angles of the two-wheelers, including their riders, were roughly the same for all three vehicles. Measured for the video frame in which the vehicle arrived at the white line, the bicycle's visual angle was 13.4°, the e-bike's 13.3° and the scooter's 12.8°.

[Insert Figure 1 here]

2.4 Procedure

Once participants were seated in front of the projection, they were informed that the experiment consisted of two blocks. For both blocks, they were supposed to put themselves in the position of a car driver at an intersection, waiting to make a left turn. This was followed by specific instructions for the TTA block, in which participants were informed that they would watch the short 4 s video clips of the two-wheelers approaching at constant speeds. At the end of each clip, the screen was blanked, and the participants' task was to indicate the moment when they felt the two-wheeler would have arrived at the white line pasted across the street surface by pressing the spacebar. Participants completed two practice trials to become familiar with the task, before data collection started. This first block was followed by a short break, before participants started with the gap acceptance block. In this block, their task was to indicate the minimum gap that they felt was acceptable to complete a left turn in front of the approaching rider. They were supposed to watch the video of the oncoming two-wheeler, and press the spacebar the moment the gap between observer and two-wheeler had reached this critical size. Again, participants completed two practice trials before the data collection started. After the experiment, they completed a short questionnaire on demo-graphic variables such as age and gender. The whole experiment lasted about 25 minutes.

2.5 Analysis

For the analysis of TTA estimation and gap acceptance, we conducted separate analyses of variance (ANOVA) for mixed designs. Bonferroni correction was used for all pairwise comparisons. Prior to the statistical analysis of TTA estimates, raw estimates were transformed into a TTA estimate ratio, which was the proportion of estimated TTA relative to the actual TTA (Schiff & Oldak, 1990):

$$\text{TTA estimate ratio} = \text{estimated TTA} / \text{actual TTA}$$

A value above 1 indicates an overestimation of TTA, a value below 1 indicates an underestimation.

3. Results

3.1 TTA estimation

In Figure 2, TTA estimate ratios are displayed for the three speed levels dependent on two-wheeler type (top left), age group (top right) and actual TTA (bottom). Full ANOVA results including all main effects and interactions are presented in Table 3. TTA estimates ratios for the scooter (M = 0.62, SD = 0.35) were smaller compared to the two bicycle types (M_{bicycle} = 0.72, SD = 0.37; $M_{\text{e-bike}}$ = 0.73, SD = 0.38, Figure 2 top left). As a result, the ANOVA showed a significant effect of two-wheeler type, and pairwise comparisons revealed a significant difference between the scooter and the two bicycle types (all $p < .001$). There was no difference between e-bike and bicycle ($p = 1.000$).

The ANOVA also revealed a significant interaction between two-wheeler type and speed. For the conventional bicycle and the e-bike, the TTA estimate ratios were highest for the 35 km/h speed level (see Figure 2, top left), whereas for the scooter, the highest TTA estimate ratios occurred at 30 km/h.

Still, overall, TTA estimate ratios increased with increasing speed, an impression that was supported by a significant main effect for speed in the ANOVA. However, pairwise comparisons showed only a significant difference between 25 km/h (M_{25} = 0.65, SD = 0.36) and 35 km/h (M_{35} = 0.72, SD = 0.36, $p < .001$), whereas there was no significant difference between these two and the 30 km/h level (M_{30} = 0.69, SD = 0.37).

We also found an effect of observers' age on TTA estimate ratios (see Figure 2 top right). Older participants had significantly lower TTA estimate ratios (*M* = 0.51, *SD* = 0.18) than the younger participants (*M* = 0.86, *SD* = 0.14), as confirmed by the ANOVA.

Although the different levels of TTA (Figure 2 bottom) were only introduced in order to provide some variation in the material to avoid undesired learning effects, and not to test a specific hypothesis, it appeared that they had an impact on TTA estimate ratios. While the ratios were more or less the same at 25 km/h, they clearly differed at 35 km/h. Accordingly, the ANOVA showed a significant difference between the three TTA levels, as well as a significant interaction between TTA level and speed. Pairwise comparisons of the three TTA levels uncovered significant differences between the 4 s conditions and the other two TTAs (both $p < .028$).

[Insert Figure 2 here]

We also found a significant interaction between two-wheeler type and TTA (see Figure 3). When the actual TTA increased, TTA estimate ratios increased as well when participants observed a conventional bicycle or an e-bike. In contrast, the TTA estimate ratios appeared to be unaffected by the three different TTAs for the scooter.

[Insert Figure 3 here]

[Insert Table 3 here]

3.2 Gap acceptance

For the analysis of gap acceptance, two participants had to be removed from the dataset, as they produced implausible values for accepted gap size. Figure 4 shows the size of the accepted gaps dependent on speed level, two-wheeler type and age group. As can be seen, younger as well as older participants tended to accept smaller gaps when confronted with the conventional bicycle ($M = 6.6$, $SD = 1.6$) or the e-bike ($M = 6.5$, $SD = 1.7$) compared to the gaps accepted in front of the scooter ($M = 7.8$, $SD = 1.6$). This impression was confirmed through an ANOVA (see Table 4 for main effects and interactions). Pairwise comparisons showed significant differences between the scooter and the two bicycles (both $p < .001$). There was no significant difference between the conventional bicycle and the e-bike ($p = .335$).

In addition, we found a significant main effect of speed, as a higher approach speed of the two-wheelers lead to smaller accepted gaps in comparison to a lower approach speed ($M_{25} = 8.2$, $SD = 2.1$; $M_{30} = 6.7$, $SD = 1.6$; $M_{35} = 6.0$, $SD = 1.2$). All speed levels differed significantly from each other (all $p < .001$).

The ANOVA also uncovered a significant interaction between two-wheeler type and speed, which appeared to be driven mostly by the bicycle. The scooter went with the largest minimum acceptable gaps for all three speed levels ($M_{25\_scooter} = 9.0$, $SD = 2.2$; $M_{30\_scooter} = 7.5$, $SD = 1.8$; $M_{35\_scooter} = 6.8$, $SD = 1.3$). The results for bicycle and e-bike differed substantially from the scooter, and were highly similar to each other for the 30 km/h and 35 km/h levels ($M_{30\_bicycle}$ = 6.2, *SD* = 1.7; $M_{30\_e\text{-}bike}$ = 6.3, *SD* = 1.7; $M_{35\_bicycle}$ = 5.5, *SD* = 1.4; $M_{35\_e\text{-}bike}$ = 5.7, *SD* = 1.4). However, at the 25 km/h level, there was a clear distinction between the two different bicycle types, as the e-bike ($M_{25\_e\text{-}bike}$ = 7.3, *SD* = 2.4) went with much smaller accepted gaps than the bicycle ($M_{25\_bicycle}$ = 8.1, *SD* = 2.4).

Different from the results on TTA estimation, the ANOVA showed no significant difference between the age groups with regard to gap acceptance ($M_{30\text{-}45}$ = 7.1, *SD* = 1.7; $M_{\geq 65}$ = 6.8, *SD* = 1.4). In Figure 4 you can see that the gap sizes are quite similar for the younger and older participants.

[Insert Figure 4 here]

[Insert Table 4 here]

4. Discussion

The primary aim of our experiment was to examine the effect of two-wheeler type on TTA estimates and gap acceptance of drivers. Our results show that the participants judged the conventional bicycle and the e-bike as arriving later than the scooter. A corresponding effect was found for accepted gap size, with participants' minimum acceptable gaps in front of a scooter being larger compared to the e-bike and the bicycle, whereas there was no difference between the two bicycle types. These results indicate that certain characteristics of the vehicle unrelated to physical size, such as the potential threat the vehicle poses, play a role in the assessment of a vehicle's approach, and a driver's subsequent crossing / turning decision.

Indeed, for stimulus material completely unrelated to the driving context, it has been suggested that perceived threat might play a role in TTA estimates. Presenting participants with pictures showing threatening and neutral content, Brendel, DeLucia, Hecht, Stacy and Larsen (2012) found reduced TTA estimates for the threatening material compared to the neutral images. In a follow up, DeLucia, Brendel, Hecht, Stacy and Larsen (2014) concluded that arousal (induced by the stimulus whose approach is to be assessed) in general is of relevance for TTA assessments. The idea that affect influences TTA estimates might be easily transferred to the road traffic domain, in which certain vehicle types, induce a higher potential threat or general arousal than others. It should be acknowledged, however, that other aspects that could impact on the perceived cost of a crash, such as the probability to be assigned blame for the crash (which, dependent on national legislation, might differ between crashes with bicycles and crashes with other motorised vehicles) can have an influence on turning decisions well.

Contrary to our expectations, we did not find clear differences between the assessments of the conventional bicycle and the e-bike. Whereas Petzoldt et al. (2017) found a strong effect with regard to minimum accepted gap size, the results of this study do not necessarily point into the same direction. It has to be noted, however, that the speed levels for which such a comparison was possible ranged from 15 km/h to 25 km/h in Petzoldt et al. (2017), whereas in this experiment, they varied from 25 km/h to 35 km/h. Given that in this study, we saw a difference between minimum accepted gap size at the 25 km/h level, but not the higher ones, it might be suspected that the effect of bicycle type is somewhat dependent on approach speed. As the proposed explanation for a difference between the two bicycles was a difference in perceived cycling effort, it might be argued that at higher speed levels, effort is rather high for both bicycle types, so that perceived differences might be reduced, compared to lower speed levels.

Alternatively, it could be argued that, given that higher speed levels are associated with longer distances from the observer, potential differences in cycling effort are difficult to see. This might be especially an issue in video based experiments (in contrast to a real world study such as Petzoldt et al., 2017), where visibility is not perfect, particularly for objects further away. At this stage, however, a final conclusion with regard to the reason for the apparent inconsistency in findings cannot be drawn.

As expected, TTA estimates for higher speed levels were higher compared to lower speeds. Although this, technically, resulted in a higher estimate accuracy, it also led to smaller accepted gaps, which is clearly worrisome. Petzoldt (2014) discussed this effect for pedestrian crossing decisions and voiced concern that this risky decision making might be difficult to modify, given the robustness of the effect in both TTA estimates and crossing decisions. Therefore, high levels of speed, especially for bicycles, might be a contributing factor to crashes at intersections as a result of misjudged vehicle approach.

As a third factor we had a look at the age of the observer, which we found to have influenced the TTA estimates. Older observers consistently provided shorter estimates than younger ones did. This is in line with results from previous studies (DeLucia, Bleckley, Meyer, & Bush, 2003; Schiff et al., 1992), and may indicate that older participants make safer decisions by using larger gaps when turning (Scialfa, Lyman, Kline, & Kosnik, 1987). However, surprisingly, the shortened TTA estimates did not translate into more conservative turning decisions, as we did not find a difference in accepted gap size between younger and older drivers. This result is somewhat contradictory to earlier studies (Alexander et al., 2002; Keskinen et al., 1998; Spek, Wieringa, & Janssen, 2006), which have shown that older drivers need more time for turning than younger or middle age drivers (Keskinen et al., 1998), and hence might choose larger gaps as a sort of compensation mechanism for age related decrements in driving ability (Yan et al., 2007). Following this argument, we would have to conclude that our participants did not show any compensatory behavioural adaptation.

It should be pointed out, however, that the experimental task, which required the participants to indicate a turning decision by pressing a button, is not fully representative of a turning manoeuvre in actual traffic. It has been argued before that "verbal or button press perceptual judgments as to whether there is sufficient time to cross a road are expected to be less accurate than judgments to actually cross, because information and movement are de-coupled" (te Velde, van der Kamp, Barela, & Savelsbergh, 2005, p. 400). The finding that older participants did not appear to compensate for potential decrements in their ability to drive a car in our experiment should therefore not be interpreted as evidence that such a compensation would also be absent in real world driving.

This potential difference between the experimental task used in the reported study and actual driving, however, must not be seen as a general lack of validity. Gap acceptance has been studied with the help very artificial visualisations (e.g. driving simulation) of the traffic scenery, just as it has been studied with video material of actual driving situations, or been observed in real traffic, and responses have been button presses as well as actual crossing or turning manoeuvres (Alexander et al., 2002; Cooper et al., 1977; Keskinen et al., 1998; Schiff et al., 1992; Yan et al., 2007). Most of the effects that can be found with the help of one of the methods have been confirmed with one or more of the other approaches. And while absolute values of accepted gap size might not be directly transferrable from the lab to the field, the differences between experimental conditions can nevertheless be considered representative of effects that would be found on the road. Therefore, it appears reasonable to conclude that our results indicate that, given that they are travelling at the same speed, the risk for crash as a result of a misjudged gap size is higher for cyclists and e-bike riders compared to a scooter rider.

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Table 1. Overview of the participants' characteristics

Age group	**N**	**M age**	**SD age**	**Min**	**Max**	**Male**	**Female**
30 - 45 years	22	37.2	4.9	30	45	6	16
≥ 65 years	22	71.3	3.7	65	78	13	9

Table 2. Overview of factors and factor levels

Age group	**Two-wheeler type**	**speed**	**TTA (only TTA part) in s**
30-45 years	conventional bike	25 km/h	4
≥ 65 years	e-bike	30 km/h	6
	scooter	35 km/h	8

Table 3. Summary of ANOVA results for the TTA estimates. Significant effects in boldface (*N* = 44).

	F	***p***	**η^2_p**
speed	**11.57**	**<.001**	**.22**
two-wheeler type *	**20.98**	**<.001**	**.33**
TTA *	**6.86**	**.004**	**.14**
age group	**14.03**	**.001**	**.25**
speed x two-wheeler type *	**3.45**	**.016**	**.08**
speed x TTA	**6.32**	**<.001**	**.13**
speed x age group	1.09	.341	.03
two-wheeler type x TTA *	**4.25**	**.009**	**.09**
two-wheeler type x age group	1.05	.356	.02
TTA x age group	1.33	.271	.03
speed x two-wheeler type x TTA*	1.27	.276	.03
speed x two-wheeler type x age group	1.52	.200	.04
speed x TTA x age group	0.67	.615	.02
two-wheeler type x TTA x age group	1.07	.372	.03
speed x two-wheeler type x TTA x age group	0.37	.939	.01

* Greenhouse Geisser correction

Table 4. Summary of ANOVA results for the accepted gap size. Significant effects in boldface (*N* = 42).

	F	***p***	**η^2_p**
speed *	**98.86**	**<.001**	**.71**
two-wheeler type *	**49.08**	**<.001**	**.55**
age group	0.37	.548	.01
speed x two-wheeler type	**3.75**	**.006**	**.09**
speed x age group	0.78	.462	.02
two-wheeler type x age group	2.89	.061	.07
speed x two-wheeler type x age group	0.55	.697	.01

* Greenhouse Geisser correction

Figure 1. Video scene of an approaching scooter

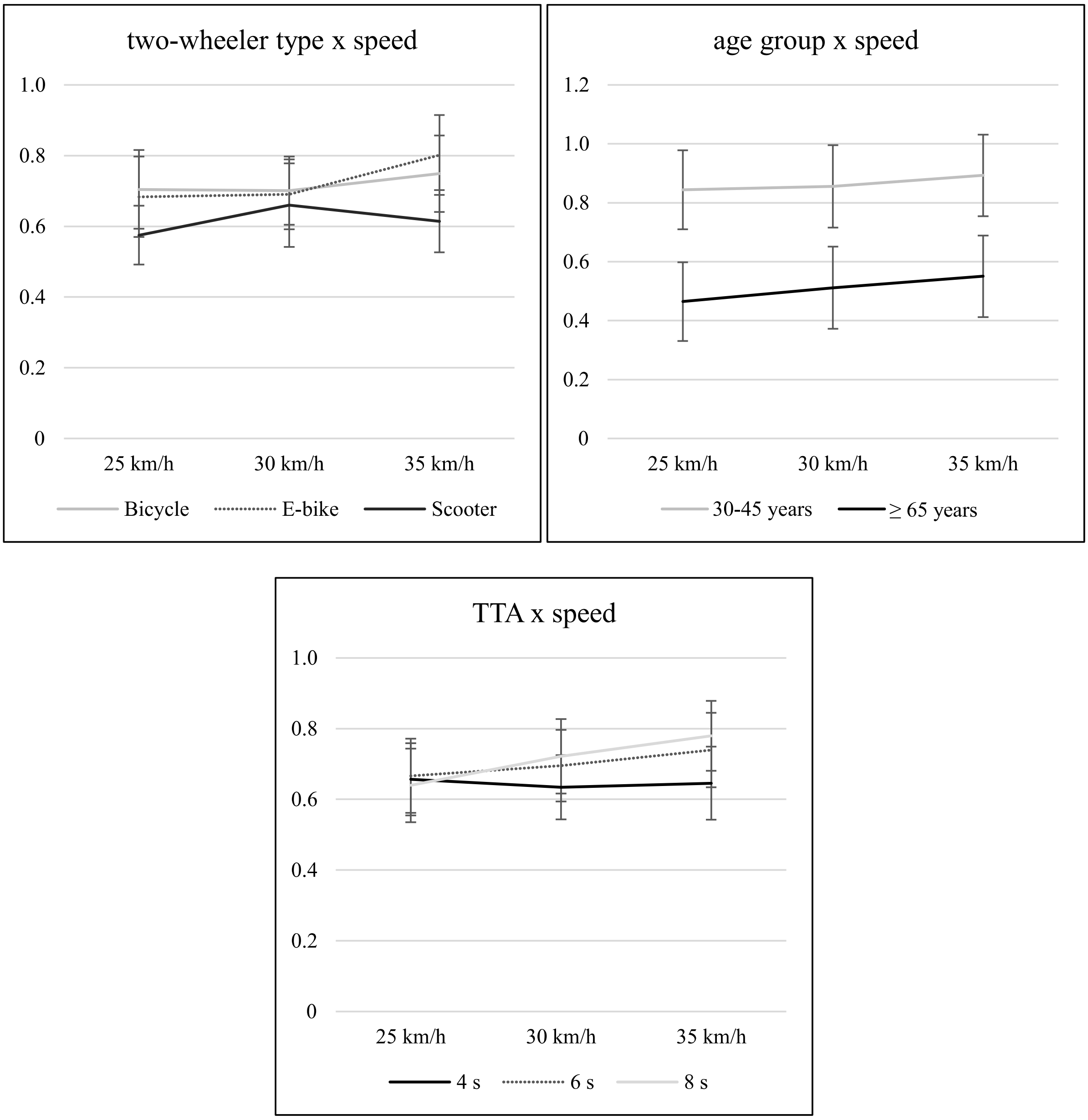

Figure 2. TTA estimate ratio for the different speed levels dependent on two-wheeler type (top left), observer's age (top right), actual TTA (bottom middle). Error bars represent 95% confidence intervals (N = 44).

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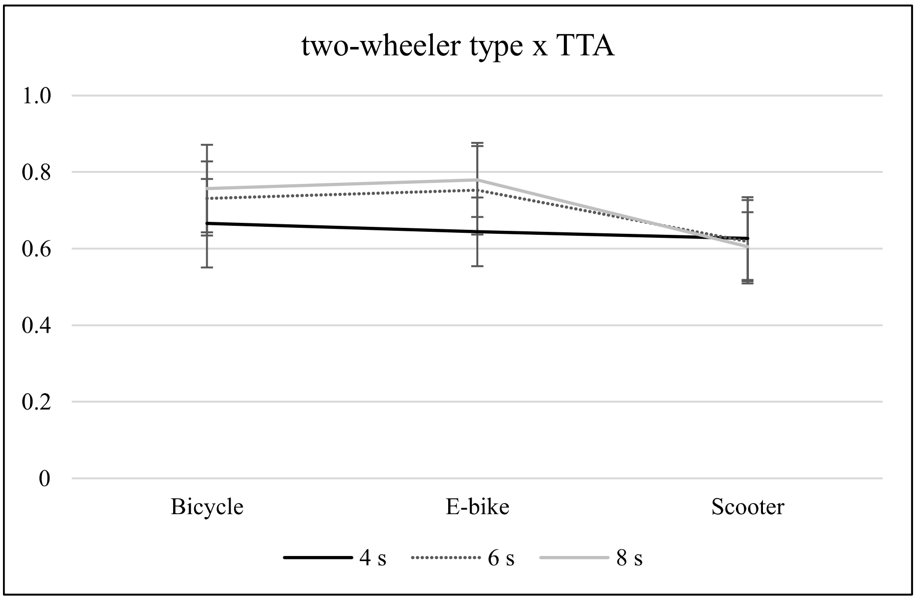

Figure 3. TTA estimate ratio for the three two-wheeler types and actual TTA. Error bars represent 95% confidence intervals (N = 44).

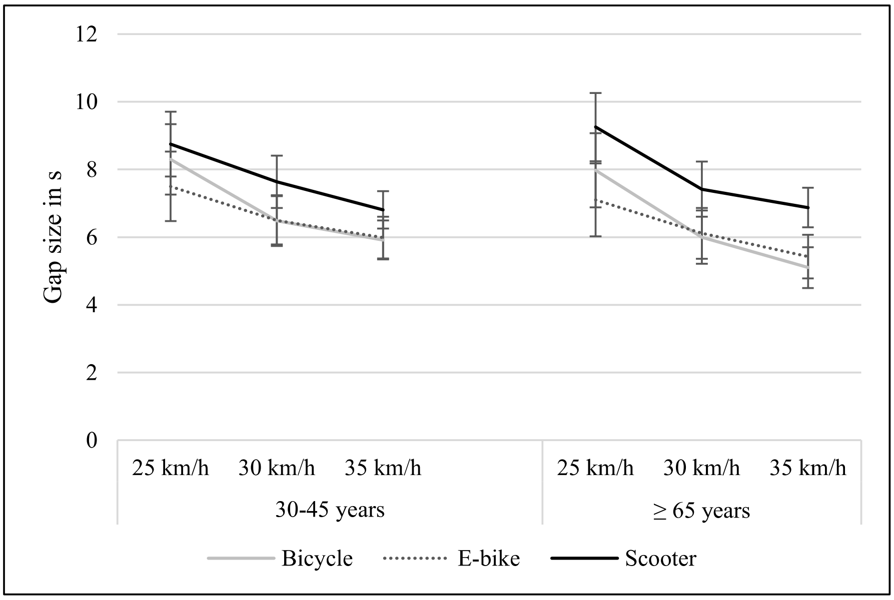

Figure 4. Gap size in s for the three speed levels and two-wheeler types, differentiated by age groups (N = 42).