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Braking Bad - Ergonomic Design and Implications for the Safe Use of Shared E-Scooters

Keywords: micromobility; e-scooters; naturalistic observation; brake ergonomics

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Abstract

Shared e-scooters are introduced as a new form of mobility around the world. Alongside this rise in micromobility, e-scooter crashes are reported, and e-scooter riders are injured and killed in traffic. Little research has been conducted on the relation between ergonomics and the safe use of e-scooters, and it is unclear whether e-scooter riders know about prevailing e-scooter related regulation and if they adhere to existing regulation in traffic. We conducted a field observation (*n*=2972) in combination with a questionnaire survey (*n*=156), to investigate the influence of ergonomics on the safe use of shared e-scooters, and to explore riders' knowledge and self-reported behavior. Riders' brake readiness, dual use (two riders per vehicle), and helmet use was registered, and specific knowledge about the braking system of e-scooters was assessed, alongside knowledge about road rules and reported past safety related behavior. Results reveal a clear effect of braking system design, with significantly more riders readying the left hand brake, in comparison with the right hand or foot brake (depending on the e-scooter model). This was found regardless of the brake-lever-to-wheel coupling, indicating that the preference for the left hand brake can be detrimental to targeted braking of the front or rear wheel. Only one third of respondents could correctly identify the basic braking system of the shared e-scooter they had last used. In addition, high shares of illegal behavior were reported by riders. Implications of these findings for the safe operation of e-scooters, their ergonomic design, and road safety regulation are discussed.

1. Introduction

In a very short timeframe, the introduction of shared e-scooters has changed the mobility landscape in countries around the globe (Gössling, 2020). At the same time, researchers find increased rates of hospitalization of e-scooter users (Namiri et al., 2020; Trivedi, B. et al., 2019) with a high frequency of head injuries (Aizpuru et al., 2019; Trivedi, T. K. et al., 2019). A plethora of potential compounding factors in e-scooter crashes and resulting injury severity have been identified. Researchers have found that between 16% and 36% of e-scooter riders arriving at hospitals for treatment of injuries are under the influence of alcohol (Badeau et al., 2019; Bekhit, Le Fevre, & Bergin, 2020; Blomberg, Rosenkrantz, Lippert, & Collatz Christensen, 2019; Puzio et al., 2020). Riders have been observed to travel against the direction of traffic (7% on roadways in Los Angeles & Santa Monica, USA: Todd, Krauss, Zimmermann, & Dunning, 2019). In countries where helmets are not mandatory for e-scooter usage, only a small share of riders uses a helmet (2% in San Jose, USA: Arellano & Fang, 2019; 6% before electric scooter helmet law in Los Angeles & Santa Monica, USA: Todd et al., 2019; 3% in Vienna, Austria: Mayer, Breuss, Robatsch, Salamon, & Soteropoulos, 2020). To a smaller extent, the practice of dual use of e-scooters (two riders standing on one vehicle) has been observed, interfering with their safe use (2% in Brisbane, Australia: Haworth & Schramm, 2019; 1% in Los Angeles, USA: Todd et al., 2019; 3% in Vienna, Austria: Mayer et al., 2020).

Germany was one of the last high-income countries to allow shared e-scooters on its streets in the Summer of 2019. To regulate this new form of mobility, Germany has enacted the *Elektrokleinstfahrzeuge-Verordnung* (eKFV, engl. *decree for small electric vehicles*), in which technical requirements for e-scooters as well as other regulatory boundaries are specified. Despite the implementation of the eKFV, increasing numbers of e-scooter rider hospitalization have been found in Germany (Störmann et al., 2020; Uluk et al., 2020).

Despite sustained international research on the safety of e-scooters, to date there is relatively little research on ergonomic aspects of e-scooters, although ergonomic aspects play a substantial role in the safe operation of other modes of transport (Bhise, 2012; Hawkins, 2006; Oppenheim & Shinar, 2011). Hence, the goal of this study is to investigate the ergonomics of the brake systems of shared e-scooters in Germany and their potential influence on riders' safety. In addition, the knowledge of e-scooter users about current regulations in the eKFV and related rider behavior is analyzed. To this end, a combination of a video-based observation of and a questionnaire survey of e-scooter users in Germany's capital and biggest city Berlin was conducted.

2. Background

2.1. Regulation of e-scooters in Germany

As there is no global regulatory framework for the introduction of e-scooters, countries and cities have enacted different sets of rules and regulations to increase the safety and safe use of e-scooters. The German eKFV mandates 14 years as the minimum age for using an e-scooter in Germany, and no driver's license of any kind is needed (eKFV §3). E-scooters maximum speed is limited to 20 km/h (eKFV §1 (1)), with faster e-scooters falling out of the eKFV's scope. A bell/ acoustic signaling is required (eKFV §6), as well as appropriate lighting and reflectors (eKFV §5). Levers for the regulation of motor power (i.e. acceleration), are required to be self-resetting to zero-acceleration after a maximum of one second (eKFV §7 (7)). Dual use is not permitted (eKFV §8). For road infrastructure, e-scooters are obligated to follow the rule of the road (right hand traffic, eKFV §11 (2)), and use dedicated bicycle infrastructure or mixed pedestrian-bicycle infrastructure within cities when it is available (eKFV §10 (1)). When no dedicated bicycle or bicycle-pedestrian infrastructure is available, e-scooters are permitted to use the road (eKFV §10 (1)). If there is no mechanism for indicating turns on the e-scooter, riders are required to use their hands for turn signaling (eKFV §11 (3)). For driving under the influence of alcohol, the same limits apply as in car use, it is illegal to drive with a blood alcohol concentration of 0.5 ‰ or higher (Straßenverkehrsgesetz, StVG §24a). Since Germany employs a graduated drivers license system and age-adjusted regulation, this general alcohol limit is lower (0.0 ‰ blood alcohol concentration) for e-scooter riders under the age of 21 and novice drivers (license for less than three years, StVG §24a). All e-scooters in Germany need to be equipped with two separately actuated brakes, which individually achieve a deceleration of at least $3.5 m/s^2$ (eKFV §4). This requirement does not necessitate that both the front and back wheel are equipped with a brake, it is sufficient when two independent levers actuate two independent brakes on one wheel. In addition, eKFV §4 (1) references §65 (1) of the general German road safety regulation (Straßenverkehrs-Ordnung, StVO) in which an "adequate brake that can be easily operated while driving" is mandated.

2.2. Braking system of e-scooters

A research need for the braking systems of the many available shared e-scooter models has been identified (Garman et al., 2020), but braking systems of e-scooter models have not been researched in detail. During the time of this study, six shared e-scooter providers were active in Berlin: Bird, Circ, Jump, Lime, Tier, and VOI (Kraftfahrtbundesamt, 2019). All provided e-scooter models fulfill the requirement of two independent braking systems, although their braking systems differ in brake lever placement as well as lever-to-wheel coupling. While some models provide two hand lever brakes on the handlebars of the scooter (Bird, Circ, Jump, Tier), other models are equipped with a foot-brake in addition to a single left hand brake (Lime, Voi) (Figure 1). While all models are equipped with a hand brake lever on the left side of the handle bar, for two models this lever actuates the front wheel (Circ, Lime), for the other four (Bird, Jump, Tier, Voi) it actuates the back wheel.

Figure 1. Handlebar of a Tier e-scooter equipped with two hand-lever brakes and a highlighted acceleration thumb-lever (left) and Lime scooter with single left-hand lever brake and foot brake for the back wheel (right).

For four of the e-scooter models (Bird, Jump, Lime, Tier), one brake lever is coupled to the front wheel and one to the back wheel, allowing the application of brake-power to both wheels. For two e-scooter models (Circ, Voi), both brake levers are coupled to the same wheel, limiting brake-power application to a single e-scooter wheel (Circ: front wheel; Voi: back wheel). Details on the brake systems are presented in Table 1. For acceleration, all e-scooter models use a variant of a thumb-lever on the right side of the handlebar (Figure 1). This acceleration lever does not lock in position and needs to be constantly actuated to keep the e-scooter moving, with non-actuation leading to the deceleration and stop of the e-scooter after a short time (as required by the eKFV).

Table 1. Brake system architecture of the six e-scooter models active in Berlin during the time of this study.

	Bird	**Circ**	**Jump**	**Lime**	**Tier**	**VOI**
E-scooter model	Bird one Germany	B1D	ES 200D	*Lime-S 3.0*	*ES 200G*	*Voiager 1*
Front wheel brake	Right brake lever	Left and right brake lever	Right brake lever	Left brake lever	Right brake lever	None
Back wheel brake	Left brake lever	None	Left brake lever	Foot-brake	Left brake lever	Left brake lever and foot-brake

Since e-scooters are relatively new, little research has been conducted on riders braking behavior and preferences, as well as general braking efficiency. Investigating brake force application, Bierbach et al. (2018) investigated the braking properties of various micromobility vehicles. With a maximum deceleration of approx. 3.1 m/s^2 the e-scooter used in the study (Egret One V3 – two hand brake levers) performed relatively poorly in comparison with a bicycle (on average 6,5 m/s^2) and a Segway (on average 4,5 m/s^2). For two wheelers in general, there is a difference in efficiency between front and back wheel braking. The act of braking on a two-wheeler shifts the dynamic wheel load towards the front wheel, hence the front wheel can exert a higher braking force on the ground than the back wheel before slipping occurs between the wheel and the ground (Wilson, Schmidt, & Papadopoulos, 2020; Wolff, 2017). Hence stronger deceleration can be achieved by using the front wheel brake on bicycles (Beck, 2004; Mordfin, 1975; Wilson et al., 2020) although the amount of deceleration further depends on the applied force on the brake lever and braking both wheels is advantageous to single wheel braking (Huertas-Leyva, Dozza, & Baldanzini, 2019). Countries have differing regulations on hand-lever-to-wheel coupling for bicycles, with Germany not regulating which lever actuates which brake. There are no studies on hand lever preferences for braking bicycles.

There are no studies on e-scooter related preferences for hand or foot brake lever usage or ergonomics, although it can be assumed, that using the foot brake necessitates more preparation, as the riders need to shift their center of gravity to use the foot brake, while the hand brake is close to the handlebars and “within reach” during normal driving.

Several challenges arise from the brake lever *placement* and *design* of shared e-scooter models active in Germany. As a general issue, the novelty of e-scooters together with the dissimilarity of brake actuator placement, either only as hand-lever brakes or as a combination of hand- and foot-actuation, prohibits the development of conformity to user expectations (DIN Deutsches Institut für Normung e.V., 2009). Hence, brake placement will have to be learnt and remembered for each individual e-scooter model, since a universal mental model for lever-to-brake coupling will be incorrect for some e-scooter models.

As a similar problem, the lack of a universal mental model for braking can lead to confusion about lever and front-/back-wheel-brake coupling. Since front- and back-wheel braking produces different brake forces, such confusion could in theory lead to an inadequate application of brake force. An additional ergonomics challenge arises for e-scooter models equipped with a hand-lever brake on the right side of the handlebar. The (eKFV mandated) need for continuous operation of the thumb-actuated throttle-lever could impede the successive actuation of the right hand brake lever. While e-scooter models equipped with a foot brake are not subject to this issue, their brake-mechanism necessitates a repositioning and lifting of the back foot to actuate the back wheel brake, involving a repositioning of the whole body on the relatively narrow e-scooter floorboard. In addition, the foot brake is rendered inaccessible in cases of dual use in which the non-driving riders stands in the back of the e-scooter.

2.3. Aims of this study

The aim of this study is to investigate traffic safety related knowledge and behavior of e-scooters as well as brake readiness in Berlin, Germany. Two hypotheses are put forward:

1. E-scooter riders are unfamiliar with the braking systems of the e-scooters they use, and hence are unable to correctly identify which brake actuator is coupled with which wheel.

2. For brake preparation movements, such as riders putting their hand on the brake lever or positioning their foot over the foot brake for a faster brake reaction, we expect that the right hand-lever and the foot brake will be observed to have significant lower brake readiness than the left hand-lever brake, regardless of brake-lever-to-wheel-coupling.

Apart from these two braking-related hypotheses, a further aim of this study is to collect additional data on the state of knowledge of riders on the prevalent road regulation for e-scooters and observe e-scooter dual and helmet use. In contrast to the brake related research hypotheses, this data collection and analysis is exploratory in nature.

3. Method

To test our hypotheses and assess additional data on e-scooter riders knowledge about prevalent road related regulation, a naturalistic observation study of e-scooter users was conducted together with a quantitative questionnaire survey at three survey sites in Berlin, Germany, between 21. September and 13. October 2019. In the fall of 2019, Berlin had the largest number of active e-scooters in Germany, with more than 11,000 deployed shared e-scooters which are used for an average of three rides a day (Tack, Klein, & Bock, 2020). The resulting three survey sites are presented in Figure 2. The observation parameters will be described first, followed by methodological details of the questionnaire survey.

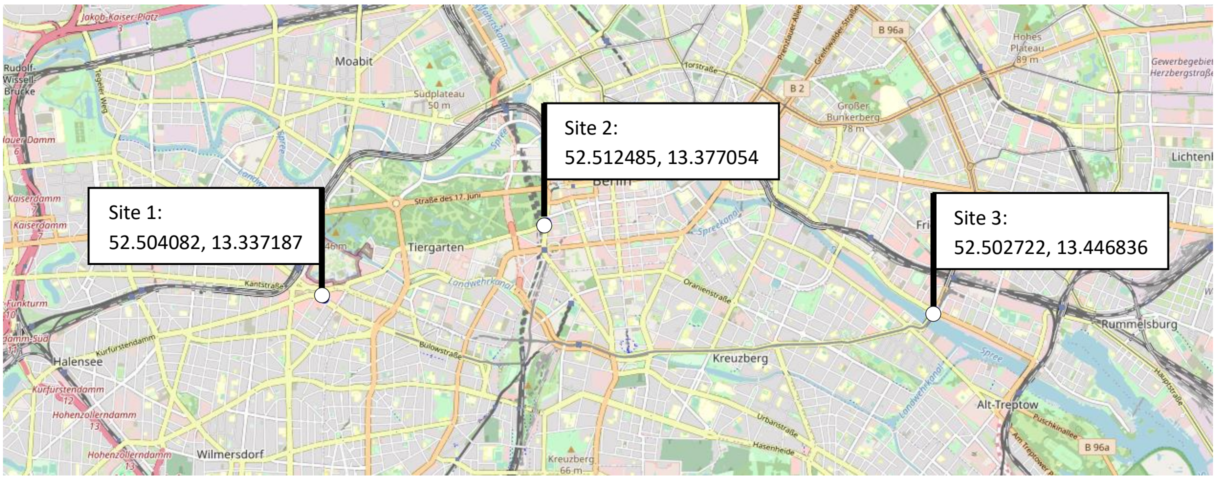

Figure 2. The three survey sites (including latitudinal and longitudinal coordinates) for observation and questionnaire distribution in Berlin (© OpenStreetMap contributors).

3.1. Observation

A camera-based observation was conducted at the three survey sites to register e-scooter riders' behavior on the street. As the General Data Protection Regulation enacted by the European Union (2016), defines a number of rules and restrictions for data collection in the public space, the observation framework was developed in collaboration with the data security officer (*Datenschutzbeauftragte* in German) of the [name of university]. Through this consultation, the video-based observation was planned in a way that minimizes the amount of personal data that is collected. The positioning of the observation cameras and the resulting viewing angles support these efforts, as they minimize the recording of road users' faces as much as possible, while still allowing the observation of e-scooter riders.

3.1.1. Observation sites

The sites for the observation were chosen based on two factors. During the time of the study, six shared e-scooter providers were active in Berlin (see Table 1), covering different areas of service for e-scooter rental. Observation sites were selected in places where all six providers were active during the time of the study. As a second objective for the identification of survey sites, the frequency of e-scooter traffic was considered, leading to the installation of cameras in the general vicinity of transport hubs, while maintaining enough distance to presume independence of observations. The distance between all sites is a minimum of 3.4 kilometers, well outside of the average travel range of e-scooter users of approximately 2 kilometers (Bai & Jiao, 2020; Tack et al., 2020). Two video cameras were used to collect video data of riders' behavior. The cameras were enclosed in a grey waterproof box and powered by a 21,000 mAh powerbank. Video data was saved on a 128GB microSD card, enabling a recording duration of approximately 14 hours. Videos were recorded with a resolution of 1920x1440 pixels and a frame rate of 30fps. Using two straps, the cameras were attached to lampposts at the observation sites at a height of 4-5 meters. In accordance with the aim of limiting the recording of personal data such as riders' faces, the cameras filmed almost straight downwards. Sample frames from the observation are presented in Figure 4 and Figure 7. The total recording duration was 274.5 hours (83.5 hours at site 1, 83.5 hours at site 2, and 131 hours at site 3), with recordings mainly conducted between 12:30 pm and 02:30 am. At all sites, an information sheet was posted, informing passersby of the ongoing observation.

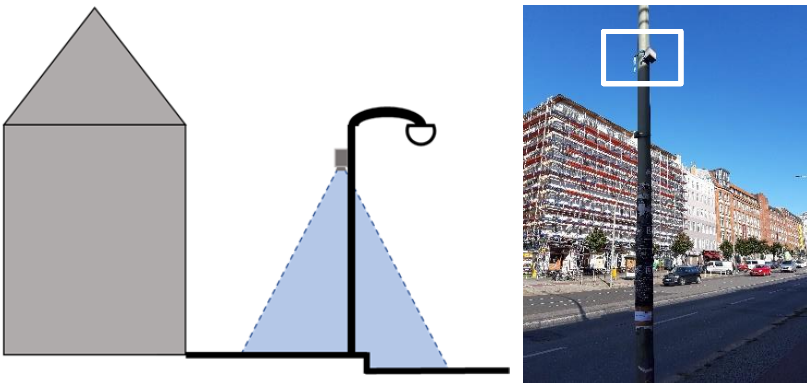

Figure 3. Representation of camera viewing angle and position (left) and picture of camera position (right).

3.1.2. Observation variables

Using the recorded video data, seven variables were registered using the software BORIS (Behavioral Observation Research Interactive Software, Friard & Gamba, 2016) for each observed shared e-scooter (private e-scooters were not registered). Variables and available codes for each variable are listed in Table 2. *Direction of travel* refers to the fact that in Germany there is only one “correct” direction for riding on a cycle path (right-hand traffic), unless an explicit exemption is made, which was not the case for the observation sites in this study. *Dual use driver position* refers to the rider in control of the handle bars, who can stand either in front of the scooter (with the passenger in the back, Figure 4) or in the back of the scooter (with the passenger in the front). The registration of hand and feet position for the assessment of brake-readiness will be explained in the following.

Figure 4. Observed dual use with the driver in the front position.

Table 2. Observational variables and available codes per variable.

Variable	Available codes
Scooter provider	Bird; Circ; Jump; Lime; Tier; Voi
Direction of travel	Correct; Incorrect
Helmet use	Yes; No; Not identified
Dual use	Yes; No; Not identified
Dual use driver position	Driver in front; Driver in the back; Not identified
Hand position (per lever)	Brake-ready; Not brake ready; Not identified
Feet position (for e-scooters with footbrake)	Brake-ready; Brake-prepared; Not brake ready; Not identified

As shown in Table 1, the e-scooter models supplied by sharing providers in Berlin are equipped with different braking systems, with some models being equipped with two hand-lever-brakes (Bird, Circ, Jump, Tier) and other models being equipped with one hand-lever-brake and one foot-brake (Lime, Voi). Hence, to identify brake readiness of e-scooter users, riders' hand and feet position was analyzed. For hand-brake levers, brake-readiness was defined as follows: if at least one digit of a hand was placed on the brake lever, the individual brake was registered as "brake-ready". For e-scooters that have two hand-brake levers, this coding is enough to assess brake readiness for both brake levers of an individual e-scooter. Examples of brake-ready and non-brake-ready hand positions are presented in Figure 5.

Figure 5. Cropped examples for brake readiness coding of hand lever brakes, not brake ready (left) and brake ready (right).

For e-scooter models with a foot lever brake on the back wheel, brake readiness was assessed by classifying the feet position on the floorboard of the e-scooter. If the two feet were placed in parallel to each other, with a lateral overlap of more than 25%, the feet position was registered as non-brake ready. If the feet of a driver were positioned so that their lateral overlap was equal to or less than 25%, the code “brake prepared” was registered, as this position allows a quicker brake reaction than a parallel feet position, although it is still necessary to reposition the braking foot to actuate the foot lever brake. Full brake readiness for the foot-brake was registered when the two feet overlapped by 25% or less (as in “brake prepared"), but in addition the heel of the back foot was raised, allowing a quick actuation of the foot brake. Examples for all three brake readiness positions for the foot brake are presented in Figure 6. To allow a direct comparison of brake readiness for hand and foot brakes, the “brake prepared” position is counted as “not brake ready” in the analysis.

Figure 6. Cropped examples of brake readiness coding for foot lever brakes, non-ready on the left, preliminary readiness in the middle, and brake ready on the right.

Because of the restricted viewing angle, caused by the top down camera position (required due to the European data privacy regulation), some caveats apply to the registration of the observational variables listed in Table 2. Within the camera’s view, only some parts of the street’s infrastructure are covered, so no general assumptions can be made on the use of a specific infrastructure for the whole street. The small timeframe in which e-scooters are visible in the camera frame does not allow a distinction between brake readiness and actual braking, as changes in speed cannot be reliably assessed. However, we argue that hand and feet positioning for both, actual braking and brake-ready hand and feet positions, can give insights into the general usage of the braking systems installed on the scooters. Additional challenges for the registration of variables are present in the video data, as e-scooters are sometimes not completely visible within the viewing angle of the camera or riders are blurred due to poor lighting, leading to an inability to register variables such as helmet use and hand position. Examples of this are presented in Figure 7. In these instances, all *observable* variables are still registered, and “not identified” is registered for *non-observable* variables.

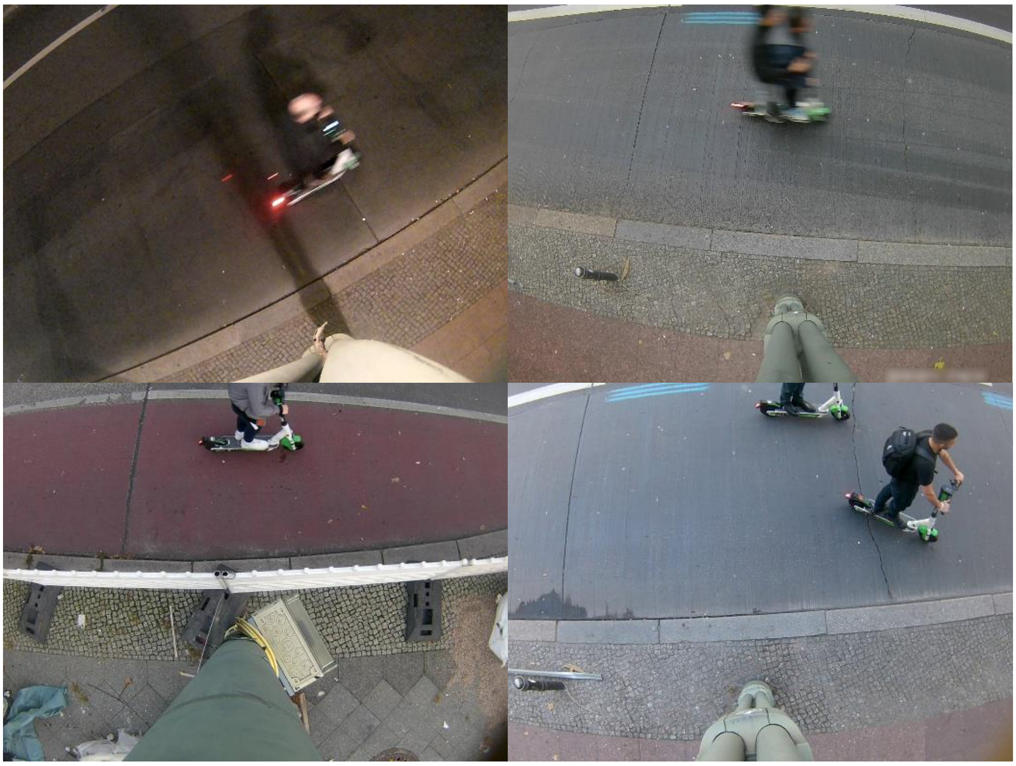

Figure 7. Examples of blurred video and e-scooter riders partly out of the video frame.

3.2. Questionnaire survey

The questionnaire survey was directly administered on a computer tablet at the three survey sites (Figure 2) around Berlin by the authors from noon to early evening hours. In addition, small paper notes with a link and a QR-code to an online version of the questionnaire were distributed at the survey sites and at the [name of university]. Participation on-site versus participation through the QR-code was not registered. The only prerequisite for participation in the survey was prior use of a shared e-scooter and there was no compensation for participation.

3.2.1. Participants

In total, *N*=156 people took part in the questionnaire survey (46=female; 107=male; 1=non-binary; 2=no answer) between the beginning of November and the middle of December 2019. The mean age of respondents was *M*=22.7 (*SD*=5.7). While 77% reported to live in Berlin, 19% reported to live in a different German city and another 5% abroad. In line with the prerequisite for participation in the survey, all respondents had used a shared e-scooter at least once. Of the 156 respondents, 62% (*n*=97) had used a shared e-scooter for three rides or less, 26% (*n*=40) had used an e-scooter once a month, 8% (*n*=12) used it once a week, 3% (*n*=5) used it multiple times per week, and only 1% (*n*=2) reported daily e-scooter use. Asked in which city they had mainly used a shared e-scooter, the majority of respondents (71%) named Berlin (*n*=111) while an approximate third of respondents (29%) placed their main use in another town (*n*=45). For 56% (*n*=87) the last e-scooter ride before the survey was more than a month ago, for 24% (*n*=37) it was within the last 30 days, for 17% (*n*=26) it was within the last 7 days, and 4% (*n*=6) had used an e-scooter on the day of the survey.

3.2.2. Materials

The questionnaire consisted of 33 questions in total. To allow participation of non-German native speakers, the German version of the questionnaire was translated by the authors to produce an English version. Of all respondents, n=134 used the German version, and *n*=22 used the English version. The questionnaire contains questions on the demographics of respondents, their general e-scooter use, their adherence to and knowledge about safety related regulation, and questions about the braking system of the e-scooter they had last used. The English items of the questionnaire can be found in the result section in the corresponding tables. The order of the items in the original presentation results from the numbering in Table 3 to 6.

4. Results

4.1. Observation

Within the 274.5 hours of video data, a total of 2972 e-scooters were observed. The main scooter provider at the three survey sites was Lime (*n*= 2143), followed by Tier (*n*= 391), Voi (*n*= 316), Jump (*n*= 70), Circ (*n*= 34), and Bird (*n*= 18). The majority of scooters was observed on a bicycle lane (*n*= 2113; 71%), followed by the street (*n*=670; 23%), and the sidewalk (*n*= 174; 6%), with infrastructure not identified for *n*=15 (0.5%) e-scooters. Of all scooters, *n*= 163 (6%) were driven against the direction of traffic illegally within the view of the camera. Dual use was observed for *n*= 92 scooters (3%), with 67 occurrences on Lime scooters, 19 on Tier, 4 on Voi, and 2 occurrences on Jump e-scooter models. Only *n*= 8 riders (0.3%) were observed to use a helmet, while non-helmet use was observed in *n*= 2670 instances (not-identified *n*= 386 (13%)).

Since every observed e-scooter model has two brake levers which can actuate one or two wheels, brake readiness is first presented in relation to the levers on each e-scooters, regardless of the lever-to-wheel coupling. Figure 8 shows the observed lever-based brake readiness for all six observed e-scooter models. Since only observed e-scooters with complete available brake-data are analyzed, the sample size (*n*=2082) is smaller than that of all observed e-scooters (*n*=2972), as for *n*=890 e-scooters (30%) at least one variable for brake-readiness detection is missing. For all registered variables, the rate of non-identification increased during evening hours (Figure 9).

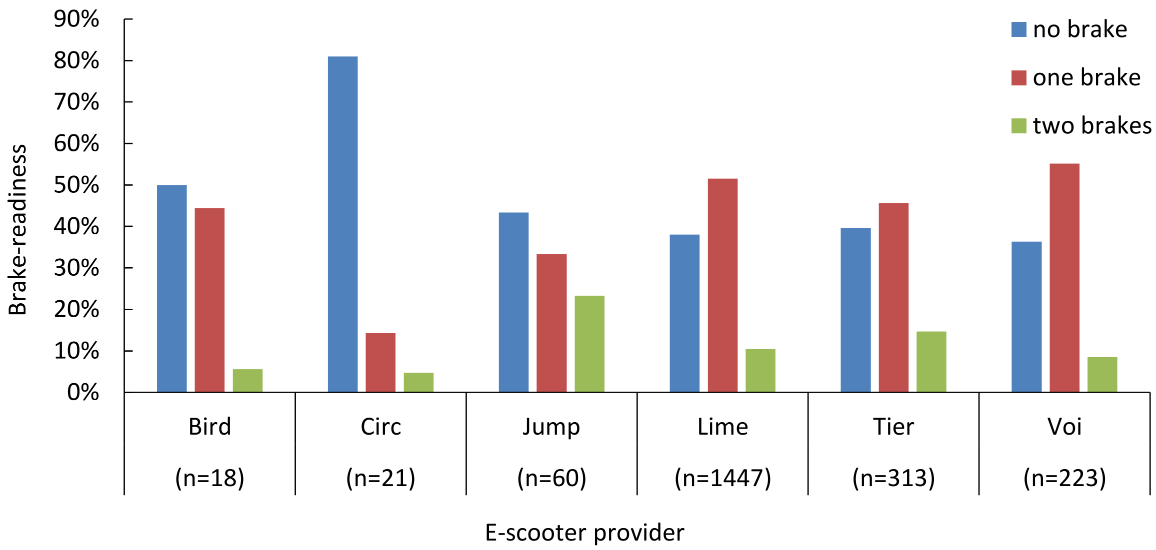

Figure 8. Lever-based brake readiness observed on e-scooter models of the six providers.

For three e-scooter models (Bird, Circ, and Jump), the majority of users is not brake-ready, i.e. users have not positioned their hands for a quick actuation of a brake lever. For the other three e-scooter models (Lime, Tier, and Voi), the majority of users is brake-ready with one brake lever. The highest lever-based brake-readiness for two brakes was observed for Jump e-scooters, where 23% of riders have both brakes ready, followed by Tier (15%), and Lime (10%). The lowest average number of brake levers readied is observed for Circ e-scooter (0.2 levers readied per e-scooter), followed by Bird (0.6 levers), Voi and Lime (both 0.7 levers); Tier (0.7 levers), and Jump (0.8 levers). For an assessment of minimum brake readiness, all e-scooters with at least one brake readied are grouped (i.e. “one brake” and “two brakes” observations in Figure 8 are added). Minimum brake readiness differs significantly between observed e-scooter providers ($\chi^2(5)=18.23$; $p<.01$). Fisher’s exact test with Bonferroni correction for multiple comparisons reveals significant differences between minimum brake readiness of Circ scooters in comparison with Jump, Lime, Tier, and Voi scooters (all $p<.0033$).

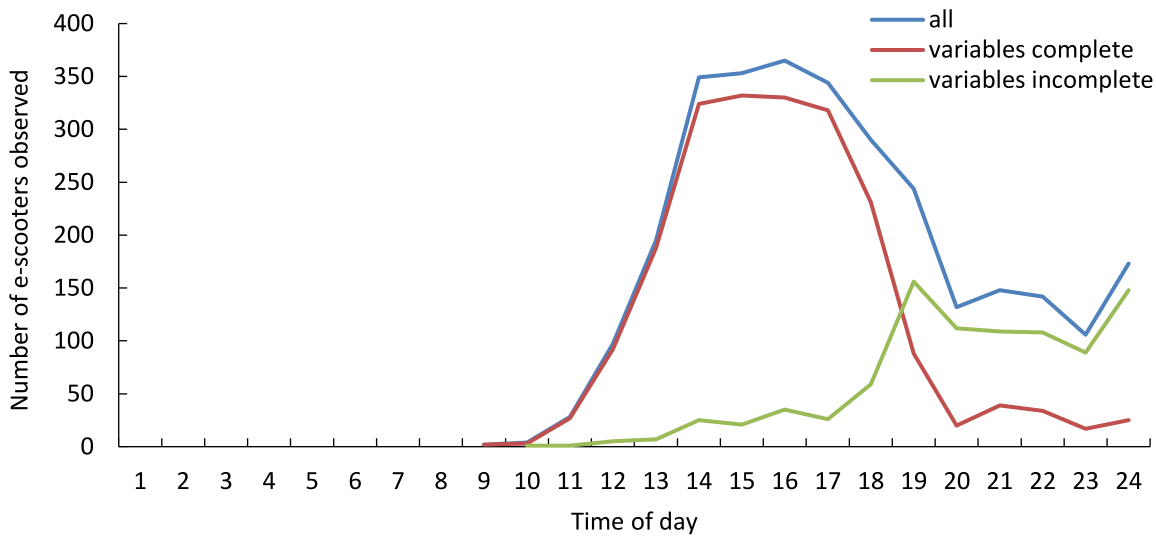

Figure 9. Number of observed e-scooters throughout the day, split for e-scooters where all variables from Table 2 were registered, and those where at least one variable from Table 2 was not identified.

To look at brake readiness in more detail, Figure 10 shows the distribution of brake lever usage for all riders with brake-readiness for *one brake lever* (*n*=1043). This brake readiness is of special interest, as riders chose to ready one lever instead of the other, while riders readying no brake or both brakes cannot be observed to prefer on lever over the other. Among all shared e-scooter riders that were observed to ready one brake, the majority readies the left hand lever brake (*n*=821), while the right hand lever brake and the foot brake are readied less often (*n*=222, see Figure 10). This difference is significant, i.e. left hand brake readying is significantly higher than 50% (z=18.52; p<.001). Observations were grouped to investigate whether riders on e-scooters with two hand brakes (Bird, Circ, Jump, Tier) show differences in brake readiness compared to e-scooters with one hand and one foot brake (Lime, Voi). For this analysis, left hand brake readiness was compared to "other lever" brake readiness (foot brake or right hand brake) between the two types of brake system. A significant difference was found in the share of left hand lever brake readying between e-scooters with two hand brakes, and e-scooters with combined hand and foot levers ($\chi^2(1)$=19.86; p<.001). Riders on two hand brake e-scooters had a more balanced ratio of left hand vs other lever brake readying (66% left hand vs 34% right hand), compared to riders on hand and foot brake scooters (81% left hand, 19% foot brake), which had higher brake readying for the left hand brake compared to other lever brake readying.

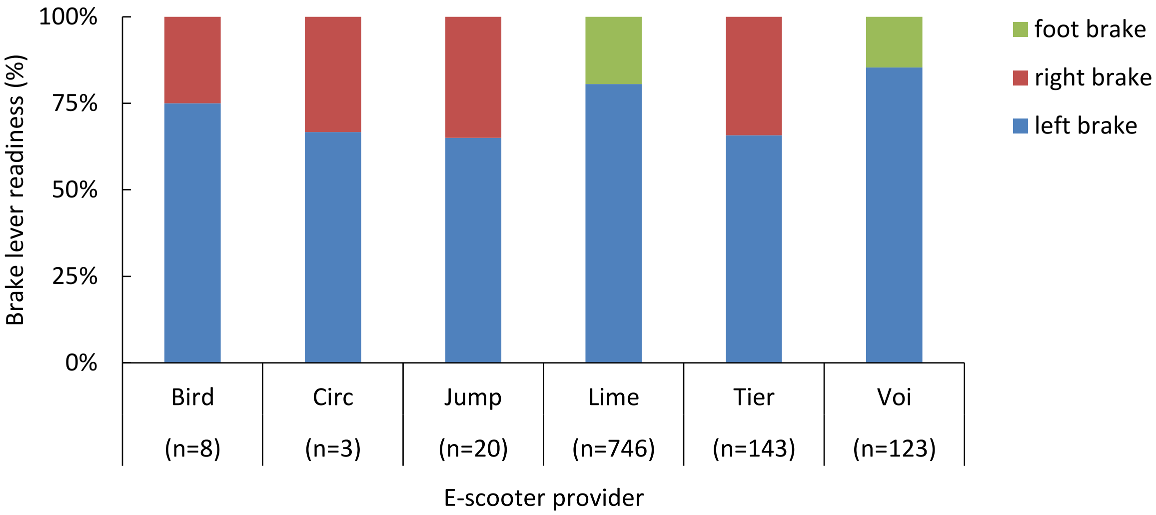

Figure 10. Observed distribution of brake levers for e-scooters where one brake lever is ready.

Apart from lever-based brake readiness (Figure 8 and Figure 10), wheel-based brake-readiness can be assessed by mapping the available brake levers to the front and the back wheel brake of scooters (using the information from Table 1). The resulting distribution is presented in Figure 11 for riders with a brake readiness of one lever, as these riders have (knowingly or unknowingly) chosen to use one brake lever which brakes an individual wheel over the other one. Descriptively, no overall pattern of front vs. back wheel braking can be observed. For Bird, Jump, and Tier scooters, a tendency for back wheel braking (left hand lever actuated) can be observed. For lime scooters, a strong tendency for front wheel braking can be observed (likewise actuated with the left-hand lever). For the Circ e-scooter model, all braking is front wheel braking, as the scooter model does not have a back wheel brake and both levers actuate the front wheel brake. Similarly, for the Voi e-scooter model, all braking is back wheel braking. Despite the fact that for Circ and Voi e-scooters, the same wheel is actuated with different levers, Figure 8 shows that 5% (Circ) and 9% (Voi) of their respective users ready two levers for potential braking, i.e. they ready two levers to brake the same wheel. This indicates that these riders are unaware of the lever-to-wheel coupling of their e-scooter.

For those e-scooter models that allow braking of the front and back wheel (Bird, Jump, Lime, Tier), we investigated whether there is a significant difference between providers and front wheel brake readiness in riders who ready one brake. Since the expected value of one cell in the contingency table was smaller than 5, Fisher's exact test was used. The test revealed a significant difference between providers in the share of brake readying of the front wheel (p<.001). To test which providers differ in the observed readying of the front brake, Fisher's exact test was used to compare individual providers, with Bonferroni correction for multiple comparison. Front wheel brake readying of observed lime scooters differed significantly from front wheel brake readying of Bird, Jump, and Tier scooters (all p<.0083).

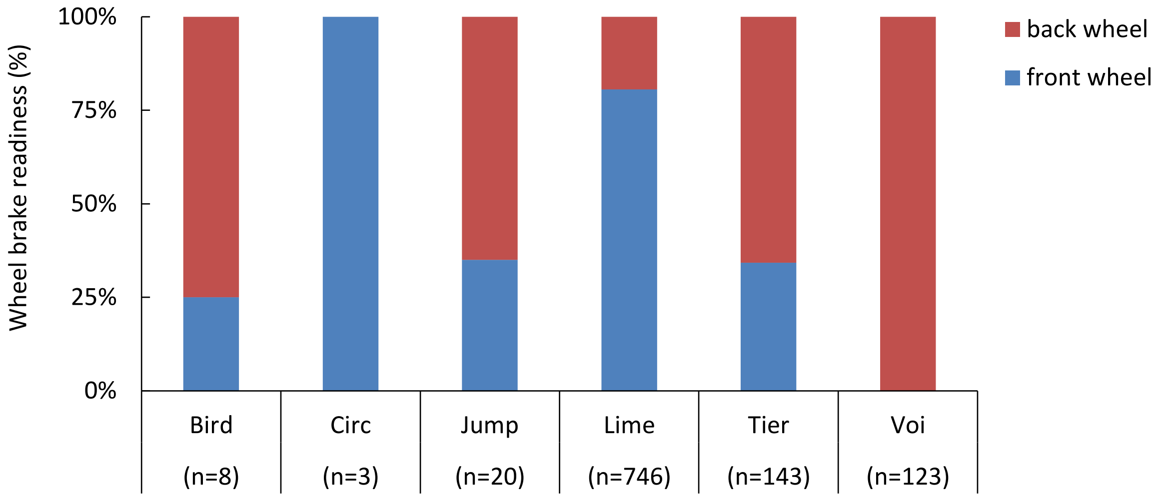

Figure 11. Observed distribution of wheel-based brake readiness where one brake lever is ready.

For dual use (*n*=92), 53 cases were observed in which the driver is in the front position with the passenger in the back of the scooter, and 39 cases were observed where the driver stands in the back of the scooter, reaching around the passenger to control the scooter. In addition to being illegal under the German Law, dual use can impact the ability to use a foot brake, if the driver is positioned in the front of the e-scooter, as drivers' access to the foot brake is blocked by the passenger (Figure 4). There were 44 occurrences of dual use where the foot brake was blocked by a passenger (1.5% of observations). For Lime scooters, there are 42 instances of dual use with the driver in the front, and 25 instances with the driver in the back. For Voi, two instances of dual use were observed with the driver in the front position, and 2 instances with the driver in the back position.

4.2. Questionnaire

All questionnaire data is presented in Table 3, Table 4, Table 5, and Table 6 showing individual questions, answering options, and percentage results of answers. The original order of items can be reconstructed by the numbering of the items. Results of the questions 1, 2, 5, 6, 7 and 10 are presented in section 3.2.1 – the characteristics of participants.

4.2.1. Driving history, and self-reported feeling of safety

Results regarding driving history, helmet use and self-reported feeling of safety are presented in Table 3. Respondents' most frequently used e-scooter provider was Lime (60%), followed by Tier (24%), Voi (6%), Circ (3%), Bird (2%), and Jump (1%), which is broadly comparable to the e-scooter provider distribution in our observational study. As similar distribution was found for the provider used during the last ride and the providers used in the past. The majority of respondents (62%) had only used one shared e-scooter provider, while 39% had used more than one shared e-scooter provider in the past. On helmet use, nearly all respondents report to never use a helmet on an e-scooter. However, around half of helmet non-users indicated that they would potentially use a helmet if it was provided by the e-scooter provider, 32% indicate potential helmet use if it was mandatory by law, and 33% report neither of the two measures would encourage them to use a helmet. Almost half of respondents indicate that their e-scooter use would decrease if there was a mandatory helmet use law.

One-tenth of respondents reported to have experienced a fall or a collision with another road user while using an e-scooter in the past. Crashes were mainly ascribed to a bad road surface, distraction, loss of control over the e-scooter, or going too fast.

Asked to rate how safe they generally feel when riding an *e-scooter* on a scale from 1 (very unsafe) to 7 (very safe), the average ratings of respondents was m=3.95 (SD=1.5). For comparison, respondents rated their perceived safety while riding a *bicycle* as m=5.61 (SD=1.1) which was significantly higher than their perceived safety on an e-scooter ($t(155)= -11.68$; $p<.001$). When respondents were asked to choose the safest road infrastructure, bicycle lanes performed best, followed by sidewalks and streets. The question regarding mostly used road infrastructure showed a high usage of bicycle lanes followed by streets and sidewalks.

Table 3. Survey questions and answers for driving history, helmet use and self-reported feeling of safety (% of answers for n=156 respondents). All items are single choice unless indicated otherwise.

Question no.	Answering options						
3. Which e-scooter sharing companies have you used before? (multiple answers)	3.8% Bird	17.9% Circ	75.6% Lime	39.1% Tier	6.4% Uber/Jump	16.0% Voi	3.8% other
4. Which e-scooter sharing company do you use most often?	2% Bird	3% Circ	60% Lime	24% Tier	1% Uber/Jump	6% Voi	4% other
11. Which e-scooter sharing company did you use during your last ride?	1.3% Bird	3.2% Circ	62.2% Lime	21.2% Tier	1.9% Uber/ Jump	6.4% Voi	3.8% Other/don't remember
8. On which road infrastructure have you ridden an e-scooter? (multiple answers)	85.3% bicycle lane			69.2% sidewalk		76.9% street	
9. Where do you ride the e-scooter the most?	58.3% bicycle lane			15.4% sidewalk		26.3% street	
15. Where do you feel the safest when riding an e-scooter?	76.9% bicycle lane			17.9% sidewalk		5.1% street	
16. Do you wear a helmet when riding an e-scooter?	98.1% never	0.6% rarely		0.0% sometimes	0.6% often		0.6% always
17. If you don't always wear a helmet, what would encourage you to wear a helmet more often? (multiple answers)	32.1% mandatory helmet law			51.3% helmet provided by sharing company		32.7% neither	
18. Would your use of e-scooters decrease, if wearing a helmet was required by law?	20.5% I don't know			33.3% no		46.2% yes	
23. How safe do you feel on an e-scooter?	5.1% 1 (very unsafe)	14.1% 2	21.8% 3	18.6% 4	25.0% 5	10.9% 6	4.5% 7 (very safe)
24. How safe do you feel on a bicycle?	0.0% 1 (very unsafe)	1.3% 2	2.6% 3	12.2% 4	23.1% 5	39.7% 6	21.2% 7 (very safe)

25. Did you ever fall or collide with another road user while using an e-scooter?	9.6% yes			90.4% no		
26. If yes, what was the reason for the accident? (multiple answers)	13.3% loss of control over the e-scooter	13.3% I was going too fast	0.0% brake(s) of e-scooter too weak	40.0% road surface was in a bad condition	0.0% other road users were reckless	20.0% I was distracted by my phone

4.2.2. Knowledge about brake-system

Table 4 shows the results of the questions regarding the knowledge about the brake-system of e-scooters. Participants were asked to think back to their last e-scooter ride and indicate if the e-scooter had one brake (i.e. for one wheel) or two brakes (for two wheels). An answering option for two brakes that both decelerate one wheel was erroneously not included, hence respondents who used e-scooters with such a brake system (Circ: *n*=3%; Voi: *n*=6%) were excluded from the following analysis, as were respondents that could not remember which e-scooter provider they used last (*n*=4%). Of all remaining respondents, 34% correctly identified that their last used e-scooter had two brakes (one for the front and one for the back wheel), while 26% of respondents falsely assumed that their e-scooter model had just one brake, and 40% did not know if their e-scooter had one or two brakes. Asked which brakes they normally use, 31% named the rear brake, 26% named the front brake, 16% reported to usually use both the front and rear brake, and 27% answered that they did not know which brake they normally use. Asked how they would intuitively brake the back wheel of an e-scooter, 22% of respondents would use the left brake lever on the handle bar, 45% would use the right hand brake lever, and 33% would use a back wheel footbrake.

Table 4. Survey questions and answers for knowledge about brake-system (% of answers for *n*=156 respondents). All items are single choice unless indicated otherwise.

Question no.	Answering options				
19. Please think back to your last ride with an e-scooter. How many brakes did this particular model have and which wheels were decelerated?	6.4% 1 brake, applies braking force to the front wheel	16.0% 1 brake, applies braking force to the back wheel	4.5% 1 brake, applies braking force to both wheels	34.6% 2 brakes, one for the front wheel and one for the back wheel	38.5% I don't know
20. Which brake(s) do you normally use?	26.9% I don't know	16.0% front and rear brake	30.8% rear brake	26.3% front brake	
21. Assuming you are using an e-scooter equipped with a brake for the rear wheel, how would you intuitively use it?	21.8% left brake lever on handlebar	44.9% right brake lever on handlebar	33.3% using my foot to press down on the brake over the rear wheel		

4.2.3. Knowledge and behavior related to traffic laws

Table 5 shows the questionnaire results for knowledge and behavior related to traffic laws. Of all respondents, 42% reported to have used an e-scooter with two people in the past. Asked if they had used an e-scooter under the influence of alcohol in the past, 39% reported to have ridden under the influence of alcohol. Regarding infrastructure usage, nearly two thirds of riders report to never have driven an e-scooter against the direction of traffic, 23% admit to have done so rarely, 10% sometimes, 3% often, and 3% always. Asked how they signal a turn, 46% use their hands, 5% signal a turn by extending their legs, and 49% report not to signal turns. One quarter of respondents could correctly identify the legal age limit for e-scooter use in Germany. Three quarters correctly answered that no driver's license is needed for e-scooter use. Asked how many people are allowed on an e-scooter at the same time, 84% of respondents correctly identified the limit of one person per e-scooter. On turn signaling, only 19% correctly answered that Germany has a law on turn signaling on e-scooter by hand. Asked whether there is a legal alcohol limit, 20% named a limit of 0.0 ‰ BAC, 46% named 0.5 ‰ BAC, 1% named 1.0 ‰ BAC, and 10% named 1.6 ‰ BAC. One fifth of respondents reported not to know the limit, and 4% indicated to think that the alcohol limit is not regulated for e-scooters. As data on driver's license ownership was not collected in this study, only the answers of an alcohol limit over 0.5 ‰ BAC, no limit, and lack of knowledge are counted as incorrect, leading to a total of 35% incorrect answers on the legal alcohol limit for e-scooters.

In two questions (no. 27 and 33), respondents were presented with multiple infrastructure options and asked to name those ones that they could legally use if all those options were available. For question no. 27, the single correct answer was the use of the bicycle lane, which was correctly identified as the sole correct answer by only 17% of respondents (although 90% included the bicycle lane as one of multiple answers). For question no. 33, no bicycle lane was presented as an option, hence e-scooters are required to use the street. More than half of the participants correctly identified the street as the sole correct answer, while 86% included it as one of multiple answers.

Table 5. Survey questions and answers for knowledge and behavior related to traffic laws (% of answers for *n*=156 respondents). All items are single choice unless indicated otherwise.

Question no.	Answering options						
12. Have you ever used a single e-scooter with two people?	57.7% no	42.3% yes					
13. Have you ridden an e-scooter under the influence of alcohol before?	61.5% no	38.5% yes					
14. Have you ridden an e-scooter in the wrong direction before?	61.5% never	23.1% rarely	10.3% sometimes	2.6% often	2.6% always		
22. How do you signal a turn?	46.2% using my hands	5.1% extending my legs	48.7% not at all				
28. How old do you have to be to use an e-scooter on a public German road?	1.3% 12	25.6% 14	25.0% 16	20.5% 18	0.0% 21	9.0% not regulated	18.6% I don't know
29. Do you need a driver's license to ride an e-scooter on public roads in Germany?	5.1% yes, a regular driver's license for cars	0.6% yes, a driver's license for e-scooters	3.8% yes, a driver's license for bicycles	76.3% no	14.1% I don't know		

30. How many people are allowed to simultaneously ride on a single e-scooter on a public German road?	84.0% 1	1.3% 2	1.9% 3	5.8% not regulated	7.1% I don't know	
31. Does Germany have a law on how to signal a turn when riding an e-scooter?	19.2% yes, using your hands	3.2% yes, by extending your legs	21.8% not regulated	55.8% I don't know		
32. Is there a legal alcohol limit for riding an e-scooter in Germany?	19.9% 0.0 Blood Alcohol Content	45.5% 0.5 BAC (same as with cars in Germany)	1.3% 1.0 BAC	10.3% 1.6 BAC (same as with bikes in Germany)	3.8% not regulated	19.2% I don't know
27. Where are you allowed to ride e-scooters in public traffic in Germany, if the following infrastructure is available? (more than one answer possible)	90.4% bicycle lane	19.2% bus lane	8.3% pedestrian area	10.3% sidewalk	76.9% street	1.3% none of these options
33. Where are you allowed to ride e-scooters in public traffic in Germany, if only the following infrastructure is available? (more than one answer possible)	22.4% bus lane	7.7% pedestrian area	12.2% sidewalk	85.9% street	10.3% none of these options	

4.2.4. Gender and safety related behaviors

To assess whether the gender of riders is related to differences in reported safety related behavior, we split survey data for riders that identified as female (*n*=46) or male (*n*=107). Resulting answers are presented in Table 6, where the Chi-square test was used to compare questions with dichotomous answers, and the Mann-Whitney U test was used to compare Likert-scale answers, due to non-normal distributions in the subsamples of male and female riders. The comparison of female and male riders in their self-reported safety related behavior did not reveal significant differences.

Table 6. Survey questions on safety related behavior for female and male riders.

Question no.	**Female**		**Male**		**Test statistics**
12. Have you ever used a single e-scooter with two people?	No 58.7%	Yes 41.3%	No 56.1%	Yes 43.9%	(χ^2= 0.09, *df* = 1, *p*=.76, *φ*=.02)
13. Have you ridden an e-scooter under the influence of alcohol before?	No 69.6%	Yes 30.4%	No 57.9%	Yes 42.1%	(χ^2= 1.83, *df* = 1, *p*=.18, *φ*=.11)
(22.) Do you signal a turn?†	No 43.5%	Yes 56.5%	No 52.3%	Yes 47.7%	(χ^2= 1.01, *df* = 1, *p*=.32, *φ*=.08)
14. Have you ridden an e-scooter in the wrong direction before? (1=never … 5=always)	Mean (*SD*) 1.39 (0.71)		Mean (*SD*) 1.73 (1.03)		*U*=2888.5, *p*=.51, *r*=0.16

16. Do you wear a helmet when riding an e-scooter? (1=never … 5=always)	Mean (SD) 1.15 (0.73)	Mean (SD) 1.01 (0.10)	*U*=2376, *p*=.16, *r*=-0.11
23. How safe do you feel on an e-scooter? (1=very unsafe … 7= very safe)	Mean (SD) 3.74 (1.44)	Mean (SD) 4.04 (1.57)	*U*=2724.5, *p*=.29, *r*=0.09

† "Yes"-answers include hand and foot signaling from question no. 22

5. Discussion

5.1. Brake related hypotheses

In this study, the safety related knowledge and behavior of e-scooter riders in Berlin was investigated in a combined observational and questionnaire survey. In our first hypothesis, we expected that riders are unable to correctly identify the type of braking system of the shared e-scooter they had last used. The results of our questionnaire survey indicate that this is correct, as only one third of respondents was able to correctly identify the braking system of the shared e-scooter they had last used. While these results could be a consequence of little experience with shared e-scooters (as more than 60% of users had used a shared e-scooter only three times or less) and a long time interval since their last use, they also indicate a lack of a simple mental model for e-scooter braking systems.

In our second hypothesis, we expected that right hand and foot brake levers would be readied less frequently than the left hand brake lever by riders. Our data indicates that this is true, as the left hand brake lever is readied significantly more often than the other available lever. For scooter models with different braking systems (all hand lever vs. hand lever combined with foot brake), the foot brake was readied significantly less often than the right hand lever. A possible reason for the preference of the left hand brake lever over the right hand lever is the positioning of the acceleration lever on shared e-scooters. For all e-scooter models, the lever for acceleration needs to be constantly actuated with the thumb of the right hand, potentially impeding the readying of any available right hand lever brake. As a similar complication in comparison to the left hand brake, the readying of the foot brake necessitates a shift in riders' body position, a prerequisite that is more effortful than the readying of the left hand brake. Further, our observational results suggest that readying the foot brake is more effortful than readying the right hand lever brake. In addition, our observational results suggest that shared e-scooter riders do not base their brake readying decision on considerations on front-wheel vs. back-wheel braking, as the location of the brake lever is the main influence on brake readying (Figure 10 & Figure 11). Our observation of riders readying two brakes that actuate the same wheel (on Circ & Voi scooters) reinforces this indication.

5.2. Additional challenges for the safety of riders

In addition to these braking-related hypotheses, our study revealed additional challenges for the safe operation of e-scooters in Germany. The observational study revealed a small share of illegal dual use of e-scooters (3%), which blocked drivers' access to the foot brake in 1.5% of observations, limiting the number of available brakes levers to one. This small share of observed dual use (registered as point prevalence, i.e. at a single time point) conforms with a large share (42%) of self-reported dual use in the past (life-time prevalence). Observed and self-reported helmet use was critically low, while self-reported e-scooter riding under the influence of alcohol was high.

A considerable number of riders is unaware of existing legal regulations on e-scooters regarding the age and alcohol limits for e-scooter use, turn signaling, and permissible infrastructure. On actual turn signaling, close to 50% of respondents report not to signal turns, which could be related to findings of riders feeling less safe when hand signaling on an e-scooter (Löcken, Brunner, Kates, & Riener, 2020). The lack of overall knowledge about e-scooter regulation, in addition to the acknowledgement of past illegal behavior may contribute to our finding that riding an e-scooter is rated as significantly less safe than riding a bicycle. The share of riders who report having had a fall or a collision (10%) while using an e-scooter is an indication that riders' assessment of the risk related to e-scooter riding could be accurate. The relatively high number of reported falls and collisions is even more alarming when factoring in the short amount of time that shared e-scooters had been allowed in Germany at the time of the questionnaire survey, and the very limited exposure to e-scooter riding that was present in the survey sample. This finding is in line with a study on e-scooter related injuries in Austin, Texas (Austin Public Health, 2019), which found that one third of 125 interviewed injured e-scooter users were first time riders.

5.3. Implications for ergonomic design and regulation of shared e-scooters

For the design of e-scooter braking systems, our findings have direct implications to brake lever placement and lever-to-wheel coupling. Our observational results indicate that shared e-scooter riders do not chose to prepare a brake lever based on considerations of which wheel to brake, but solely on the placement of the brake levers on the e-scooter. The preference for readying the left hand brake lever indicates a higher usability of this brake lever in comparison to the right hand lever and the foot brake. The most likely reason for this preference lies in the placement of the right thumb actuated throttle lever which needs to be continuously actuated, and a comparatively high effort to ready the foot brake. This knowledge can be used by e-scooter providers and manufacturers to design their braking system more intuitively. In light of the higher efficiency of front wheel braking, it seems advisable to couple the left hand brake lever with the front wheel of e-scooter models (as Circ and

Lime already do) and not to the back wheel (as Bird, Jump, Tier, and Voi do). However, further research is needed to investigate the relation of front- and/or back wheel braking and e-scooter stability.
The indications of lack of knowledge of lever-to-wheel coupling of riders calls into question the practice of coupling two separate brake levers to the same wheel (as Circ and Voi do). While this “same wheel dual braking” complies with the letter of the law of e-scooter regulation in Germany (eKFV), it prevents riders from decelerating both wheels of the e-scooter, reducing the overall potentially applicable brake power. In addition, brake force application to both wheels, actuated through on lever (preferably on the left side of the handlebar) could be used to increase potential brake force available to riders. For the legislative regulation of braking systems, it seems worth investigating how brake levers actuated by the right hand or through a footbrake stand in compliance with the general German road safety regulation (StVO), which requires an “adequate brake that can be easily operated while driving”. While experimental studies need to investigate the share of *use* of the right hand and foot brake, our results indicate that these brake lever types will not be easily and quickly actuated in emergency braking situations. To support the knowledge of shared e-scooter riders about the braking systems of a given e-scooter, it seems advisable to add consistent color- and haptic coding of front and back wheel brake levers. E.g. regulators could mandate that the back wheel actuating brake lever should be colored darker and be tactilely coarser than the brighter and smoother front wheel actuating lever.

5.4. Limitations

There are a number of limitations to this study. In the observational study, brake readiness was registered, but not actual braking. While we argue that brake readiness translates to actual braking with the readied brake levers, an observation of individual e-scooters over a longer time span is needed to show what share of brake readiness at a given brake lever translates to actual braking at that individual lever. This validation of our observational approach is needed especially for the actuation of the foot brake, where readying of the brake is not as apparent as for the hand lever brakes. For the analysis of the video data, a number of variables could not be registered due to blurry video and riders being partly out of frame (Figure 7). In addition, the number of e-scooters without complete data for all variables increased during evening hours (Figure 9), potentially obscuring more dangerous behaviors at evening hours, and prohibiting an analysis of the influence of time of day on riders behavior. Future studies should use more light-sensitive (or infrared) cameras to minimize motion blur. As the sample in the questionnaire survey was relatively small and young, future studies should aim for larger sample sizes with a broader age-range, to produce results that are more representative, especially in the light of the relation between age and traffic rule violations and crash rates (Alver, Demirel, & Mutlu, 2014). As riders were surveyed mostly between noon and the early evening, future studies should expand survey times to later hours, to collect a more comprehensive sample of e-scooter users. Riders surveyed in our study had comparatively little experience in e-scooter use, as shared e-scooters had just been introduced in Germany. While e-scooter use experience will further increase in Germany and future studies will potentially not have this issue, they should nonetheless aim to collect data from riders that use e-scooters more frequently, to check whether frequency of use influences knowledge about braking systems and applicable regulation. In addition, future studies should explore if different e-scooter providers are used by different types of riders. While the cost structure and general marketing of providers in Germany did not initially target different user groups this might change once providers try to differentiate themselves from their competitors. To assess other potential influences on left- versus right-hand brake lever usage, handedness of riders should be assessed in future studies.

5.5. Conclusion

In conclusion, this study revealed a number of factors in the ergonomic design of shared e-scooter braking systems which can influence the safe use of e-scooters in the road environment. Legislative bodies and e-scooter providers need to consider these findings to increase the safeness of e-scooter use. In addition to these ergonomics challenges, our questionnaire survey revealed a critical lack of knowledge in e-scooter users. Public education campaigns coupled with better information provision through e-scooter providers on applicable laws and regulation are necessary to increase users' knowledge on the safe use of e-scooters on the road.

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