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Errors and violations in relation to bicyclists' crash risks: Development of the Bicycle Rider Behavior Questionnaire (BRBQ)

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ABSTRACT

Promoting bicycling has several health benefits at the individual- and population-level. However, safety concerns for bicyclists is one of the main hindrances for bicycling. Little work has explored aberrant riding behavior, and to the best of our knowledge, no instrument that measures aberrant behavior among bicyclists has been reported in the literature. This study reports the psychometric properties of a newly designed measurement instrument, the Bicycle Rider Behavior Questionnaire (BRBQ) that follows methodological approaches of motorized vehicle user behavior questionnaires. The BRBQ is a 34-item questionnaire that relies on Principal Component Analysis with Varimax Rotation to identify dimensions of aberrant behavior and ultimately predict self-reported multi-vehicles crashes. We illustrated this approach on a sample of 306 bicyclists in Iran and developed a five-dimension solution that explained 51% of the total variance. The dimensions were termed: "Stunts and Distractions", "Traffic Violations", "Notice Failures", "Control Errors", and "Signaling Violations" with Cronbach's alpha ranging from 0.70 to 0.84. On average, males reported more Stunts and Distractions than females, while females reported more Control Errors than males. Bivariate correlations between dimensions and riding experience indicated that as years of riding experience increased, aberrant behaviors of riders declined. Further, as riders grow older, the occurrence of their reported Control Errors and Signaling Violations increased. Logistic regression results showed that Traffic Violations, Stunts and Distractions, and Signaling Violations were the predictors of at-fault self-reported multi-vehicle crashes. Traffic Violations, Control Errors, and Notice Failures were the predictors of all self-reported multi-vehicle crashes. The BRBQ was found to have feasible psychometric properties and had good criterion validity that supports the original theoretical taxonomy of human errors. The findings present a sample of Iranian bicyclists and need further validation in other settings.

1. Introduction

Bicycling is considered as a health-promoting active mode of transport, consistent with the goals and policies of sustainable transport use. As a substitute of motorized transportation, bicycles can help to reduce negative externalities of the transport system. Moreover, bicycling provides several individual and public health benefits for the bicycle riders (Brown et al., 2016; Fishman et al.,

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2012; Schepers et al., 2015). Bicycling has been increasing in European and North American cities, and in recent years, the number of bicycle-sharing programs and bicycle-related facilities have increased globally, particularly in Asia, Europe and North America (EPI, 2013a, 2013b; van Heijningen, 2016; Wegman et al., 2012). These changes in supply and demand sides may increase the number of bicycles on the roads. Bicycle safety is one of the main concerns that may constitute a barrier to the increased use of this mode (Chataway et al., 2014; Dill and McNeil, 2013). Bicycling also affects individual health in two ways, first by inhibiting uptake that reduces individual physical activity. Second, bicycling affects traffic crash casualties, mainly due to the fact bicyclists have higher crash risk in comparison to other road user (Wegman et al., 2012).

There is a relatively large literature on crash risk for bicyclists and two factors tend to reduce risk, the increase in volume of bicyclists (i.e., safety in numbers) (Harwood et al., 2008; Robinson, 2005; Schepers and Heinen, 2013) and providing safe infrastructure for bicyclists (See Ling et al., 2017; Wegman et al., 2012). Moreover, a relatively large body of studies has shown that human factors have a critical role in traffic crashes, and bicycle crashes are not an exception. Nevertheless, few studies investigated bicyclists' role in road safety. In the eyes of other road users, bicyclists often manifest unexpected behaviors and fail to obey traffic rules which could result in higher crash rates among road users (Langford et al., 2015; Wegman et al., 2012). One feasible alternative to reduce crash risk among bicyclists is to implement non-enforcement countermeasures such as road safety campaigns.

In an early study, Elander et al. (1993) categorized drivers' human factors into driving style and driving skill. Several self-report instruments have since been developed to measure driving style. The Driver Behavior Questionnaire (DBQ) is one of the most widely used instruments. It is based on the theoretical taxonomy of human errors and follows the idea that aberrant behaviors could be categorized into errors and violations (Reason et al., 1990). Dozens of studies used this theory to identify aberrant behaviors among motorized road users (De Winter and Dodou, 2010). Yet, no studies or instruments have been developed to investigate aberrant behavior among bicyclists. The DBQ identified different types of behaviors among drivers, such as the original three-factor solution (violations, errors, and lapses) (Aberg and Rimmo, 1998; Parker et al., 1995) and four-factor solution (aggressive violations, ordinary violations, errors, and lapses) (Gras et al., 2006; Lajunen et al., 2004; Lawton et al., 1997).

Researchers defined *errors* as "failure of planned actions to achieve their intended consequences" and *violations* as "deliberate deviations from those practices believed necessary to maintain the safe operation of a potentially hazardous system" (Reason et al., 1990). *Errors* were further distinguished into slips, lapses, and mistakes. Slips are actions that do not have the intended consequences, while lapses refer to memory failures (Parker, 2007). Mistakes refer to failures in the plan of action; even if execution of the plan is done correctly, the intended outcome is not achieved (Parker, 2007). *Violations* may occur due to several reasons, and these behaviors have accordingly been found to split into different dimensions. Lawton et al. (1997) split violations into aggressive violations and ordinary violations. Aggressive violations contain an interpersonally aggressive component, and ordinary violations are deliberate deviations from safe driving without reflecting aggression. Although different structures have been found, the distinction between unintentional errors and intentional violations appears to be stable and independent of respondents' age, gender, country, or the type of vehicle they use (De Winter and Dodou, 2010; De Winter, 2013).

By applying the theoretical taxonomy of human errors, Elliott et al. (2007) developed the Motorcycle Rider Behavior Questionnaire (MRBQ). They identified a five-dimension solution consisting of Traffic Errors, Control Errors, Speed Violations, Performance of Stunts, and Use of Safety Equipment. In a Turkish application, Özkan et al. (2012) identified a similar structure. In a shorter and different version of the MRBQ, two dimensions of aggressive and ordinary violations were found in a sample of Chinese motorcycle riders (Cheng and Ng, 2010).

Different types of behavior have been found to predict self-reported crashes (Af Wåhlberg et al., 2015; De Winter and Dodou, 2010). Several studies that focused on driving found that violations were an important predictor of self-reported crashes (Gras et al., 2006; Hezaveh et al., 2017; Kontogiannis et al., 2002; Nordfjærn et al., 2015; Özkan et al., 2006). On the contrary, the empirical accounts have not demonstrated a consistent association between self-reported crashes and errors among drivers (Nordfjærn et al., 2015; Özkan and Lajunen, 2005; Parker et al., 1995; Warner et al., 2011). Among motorcyclists, traffic errors were the main predictors of crash risk. Control Errors and speed violations have also been found to be significant predictors of crashes where the motorcyclist accepted a degree of fault (Elliott et al., 2007). Özkan et al. (2012) reported that stunts were the main predictors of motorcyclists' crashes (i.e. rider hit another road user or an obstacle).

As bicycling becomes a more important strategy toward sustainable mobility, understanding safety behavior of bicyclists becomes more urgent. The aim of this study was to develop a new instrument, the Bicycle Riders Behavior Questionnaire (BRBQ), to measure bicyclists' behavior based on the taxonomy of human error. The dimensional structure and validity of the instrument were tested in relation with self-reported crashes. This instrument enables researchers to investigate self-reported behaviors among bicyclists and to identify behavioral dimensions that are highly associated with self-reported crashes. The results could offer information that may be utilized by enforcement or educational initiatives to lower the crash risk among bicyclists.

1.1. Hypothesized dimension structure of the BRBQ

Bicycles and motorcycles have common structures and mechanism of crashes. Despite differences in bicycle speed, weight, and source of power; bicycles and motorcycles are both single-track vehicles and their kinematics have many common fundamental attributes that are fundamentally different from other wheeled vehicles (Pacejka, 2005). Bearing in mind the differences and similarities, we expect that the structure of BRBQ has common dimensions with the MRBQ.

Mounting and dismounting onto the bicycle, balancing, steering and riding on uneven roads all impose different challenges to the rider (Tan et al., 2014). Particularly, compared to a four-wheeler, it will be more difficult to recover from a control error when riding a two-wheeler. Hence, items related to maintaining the balance of the vehicles needed to be included in the BRBQ.

Similar to motorcycles, bicycles enable their riders to perform stunts (e.g., pulling wheelies) on roads more readily than other transportation forms (Elliott et al., 2007). With the purpose of decreasing their risk injury, riders may use safety equipment, including protective clothing and helmet, which reduce the likelihood of severe injuries (Attewell et al., 2001). Therefore, performing stunts and safety equipment should be included in the proposed BRBQ.

Another aspect which needed to be measured was signaling behaviors. Unlike other vehicles in the transportation system, bicycles are not equipped with indicators, brake lights, and horn. Riders use hand signals and audible message to communicate with other road users. Using hand signals could reduce crash risk with other vehicles, but could also introduce Control Errors. Taking these factors into consideration, the present study included items associated with Control Errors, stunts, use of safety equipment, and signaling to other road users in addition to items that measure ordinary errors and violations to develop the BRBQ instrument. The rest of the paper discusses the methods used to develop and deploy the BRBQ instrument and the statistical methods associated with developing dimensions from the questionnaire, focusing on a sample of 306 bicyclists. The results of the statistical analysis are presented, followed by a discussion of the method and results. Finally, the paper closes with concluding remarks.

2. Methods and materials

2.1. Questionnaire

The main contribution of this paper is the development and testing of a standard questionnaire aimed at bicyclists, the BRBQ. This parallels past works, the MRBQ and the DBQ. The first section of the questionnaire included items about demographic characteristics, bicycle riding habits, and the crash records of the respondents. Demographic characteristics included gender, age, marital status, and educational level. Riding habits covered questions about number of years riding a bicycle (bicycling experience), riding hours per week, the purpose of riding a bicycle (i.e., recreational, professional, commuting to work/shopping/school), and riding context (i.e., urban, rural, or mountain).

Respondents reported their crash involving another road user (i.e., multi-vehicle crash) in two periods in the last three years and period prior to those three years (i.e., crash history). Crash records included questions about the overall number of multi-vehicle crashes, and number of crashes that riders was identified as being at-fault by a police officer in a multi-vehicle crash (i.e., at-fault multi-vehicle crash).

The second part of the survey included the behavioral instrument. The BRBQ was developed in two steps. First, a questionnaire was developed based on the MRBQ (Elliott et al., 2007) drawing from similar aberrant behaviors among bicyclists and motorcyclists. The original DBQ (Reason et al., 1990) was used to include perceptual errors and violations (e.g., red light running). Last, we drew from available literature on bicycle safety to identify the aberrant behavior of the bicyclists and to establish behavioral questionnaire with 35 items.

In the second step, the preliminary BRBQ was discussed in a focus group consisting of transportation engineers with expertise in road safety. We added or removed items from the BRBQ based on feedback. After amendments to the BRBQ, a pilot survey was deployed. A questionnaire with 39 items was distributed to a sample of 100 bicyclists. The respondents were asked to report how often they performed each aberrant behavior (e.g., almost lost control due to the presence of an obstacle in the road surface) on a five-point Likert scale (1: never, 5: nearly all the time). Principal Component Analyses (PCA) were conducted on the pilot sample. Items that had no loading on the initial extracted dimension (cut-off point 0.30) from the pilot study, and had an average numerical value close to one, were excluded from the BRBQ instrument. During the pilot study, items related to wearing safety equipment failed to load in any dimensions. Accordingly, these items were removed from the main questionnaire. The questionnaire that was used in the main study consisted of 34 items. Importantly, the BRBQ could be modified to reflect characteristics of the bicycling community where deployed. Our study was based in Iran, but the questionnaire and analytic approach could be used in other geographic and demographic contexts as they relate to bicycling behavior.

2.2. Sampling

A convenience sample was drawn from amateur, semi-professional, and professional bicycle clubs in Iran. This sample does not likely represent average bicyclists, but still, allows for testing of the BRBQ instrument. In most cases, these clubs used social networks to reach their members. After contacting the administrators of the clubs, a web-based Persian questionnaire was uploaded in Google Docs and the link to this questionnaire, along with an invitation letter, was shared with members of the clubs. The criterion for completing the questionnaire was a minimum of one hour of bicycling per week in Iran. The questionnaire was active for four weeks in June 2016. Among an unknown number of visits to the invitation letter, 771 clicks on the link were registered. A total of 306 respondents filled out the questionnaire completely, which reflects a 40% response rate.

2.3. Statistical procedures

Statistical analyses were performed using SPSS 22.0 and STATA 13. Kaiser–Meyer–Olkin (KMO) was used to test whether the sample data met the requirements for Principal Component Analysis (PCA). PCA with Varimax rotation was conducted to identify the dimensional structure of the BRBQ. Kaiser's criterion, the Cattell scree plot and the interpretability of the dimensions were used to determine the number of components. In addition, Cronbach's alpha reliability coefficients were calculated for assessing the internal consistency of the BRBQ scale scores. Non-parametric tests (i.e., Mann-Whitney U and Kruskal-Wallis) were run to compare the

Table 1
Sample characteristic.

Variable Category		Frequency	(%)	Variable Category		Frequency	(%)
Age (years)	24 and younger	64	20.92	Crash History	0	175	57.19
	25-35	136	44.44		1	131	42.81
	36-49	87	28.43	Education	Some Level of High school Degree	31	10.10
	50 and older	19	6.21		Diploma	65	21.20
Frequency of Multi-Vehicle Crashes in the Past Three-Year period	0	139	45.42		Associate Degree	29	9.50
	1	47	15.36		Bachelor Degree	111	36.30
	2	48	15.69		Master Degree	60	19.60
	3	26	8.50		PhD Degree	10	3.30
	4	46	15.03	Purpose of Bicycling	Recreational	178	58.17
Frequency of the Multi-Vehicle At –fault Crash Frequency in the Past Three-Year Period	0	196	64.05		Professional Bicycling	49	16.01
	1	42	13.73		Others	79	25.82
	2	34	11.11	Context of Riding	Rural Context	45	14.70
	3	13	4.25		Urban Context	218	71.20
	4	21	6.86		Mountain Context	43	14.10

differences between groups on the BRBQ dimensions.

We modeled the relationship between multi-vehicle crash occurrence (all self-reported multi-vehicle crashes and at-fault self-reported multi-vehicle crashes) and BRBQ dimensions using logistic regression models. Riding context, riding experience, riding hours per day, riding purpose, and history of crashes along with BRBQ dimensions were modeled simultaneously.

3. Results

3.1. Sample characteristics

Table 1 shows the characteristics of the samples. The sample consisted of 72 females (24%) and 234 (76%) males. The average age of the respondents was 33.1 years (range 16–72, SD = 10.0) with 10.20 years of riding experience (range: 1–39, SD = 9.40), and 9.1 hours per week (range: 1–25, SD = 7.20). 56% of the respondents reported at least one bicycle crash (M = 1.64 crashes per respondent, SD = 2.15). In addition, 36% of the respondents indicated that they had been involved in at least one at-fault crash (M = 0.84 at-fault crashes per respondent, SD = 1.50); this indicated that bicyclists were at-fault in 52% of their self-reported multi-vehicle crashes. In addition, 44% of the respondents reported that they had experienced at least one crash before the three-year period. Comparisons of self-reported multi-vehicle crashes by gender did not show any significance differences (for all multi-vehicle crashes: $U = 9089.0$, $p < 0.590$; for at-fault multi-vehicle crashes: $U = 8176.0$, $p < 0.659$). As presented in in Table 1, 69% of the respondents had a university degree, and 58% of respondents used bicycling for recreational purposes. Moreover, urban settings constituted the most prominent context of riding.

The mean and standard deviation of the BRBQ questions are shown in Table 2. Failure to use hand signals to communicate with other road users was among the most frequent reported behaviors. Distractions by music and cell phones as well as aggressive violations towards other road users were also among the most reported behaviors. Riding under the influence of alcohol and drugs were among the least reported behaviors in our study in Iran.

3.2. Dimension structure of the instrument

The KMO measure of sampling adequacy for the current sample was 0.82 (meritorious), which supported that the sample was suitable for performing PCA (Beavers et al., 2013). Table 3 shows the result of PCA with Varimax rotation. A five-dimension solution was identified which explained 52.10% of the total variance.

The first dimension included eleven traffic violations; two yielding violations, three emotional violations, three speeding violations, and three violations related to riding in prohibited roads for bicyclists. This dimension was termed “Traffic Violations” which accounted for 23.08% of the total variance. The Cronbach’s alpha for this dimension was 0.84. Three items related to stunts and three distractions (i.e., physical or mental) loaded in the second dimension. Hence, this dimension was named “Stunts and Distractions”. This dimension accounted for 9.07% of the total variance with Cronbach’s alpha of 0.79. The third dimension consisted of five items related to Notice Failures which accounted for 7.38% of the total variance. This dimension included items regarding riders’ failure to notice other road users (e.g., pedestrians crossing or waiting to cross the street). All these items may lead to a sudden reaction which could cause dangerous situations. Hence, this dimension was termed “Notice Failure”. The Cronbach’s alpha for this dimension was 0.78. Five items related to control the bicycle loaded in the fourth dimension, hence this dimension was termed “Control Errors”. This dimension accounted for 6.55% of the total variance and had a Cronbach’s alpha of 0.77. Three violations related to communication with other road users loaded in the fifth dimension. This dimension was termed “Signaling Violations”. Signaling Violations accounted for 5.24% of the total variance and had a Cronbach’s alpha of 0.76.

Table 2
Means and Standard Deviations of the BRBQ items.

Items	M	SD
Fail to give appropriate signal for stopping the bicycle	3.67	0.08
Fail to give an audible signal when overtaking pedestrians	2.87	0.08
Listen to music while riding	2.73	0.09
Fail to give hand signals (at least two seconds preceding the beginning of the movement) for left & right turns	2.71	0.08
Have felt frustrated by other road users	2.67	0.07
Felt angry and aggressive towards another road user	2.17	0.07
Almost lost control due to obstacle presence in road surface	2.10	0.06
Been distracted or pre-occupied to the point that you did not that the vehicle in front of you slowed and you had to brake hard to avoid a collision	2.10	0.07
Ride in prohibited expressways, drives, highways, interstate routes, bridges, and thruways unless authorized by signs	2.09	0.07
Talk on the phone while riding your bike	2.09	0.07
Fail to notice someone stepping out from behind a parked vehicle until it is nearly too late	2.05	0.07
Speed up to beat the traffic light turning red	2.00	0.07
Riding without having at least one hand on handlebars at all times	1.99	0.07
When riding at the same speed as other traffic, you find it difficult to stop in time when a traffic light has turned against you	1.98	0.06
Get involved in unofficial races with other riders or drivers	1.92	0.07
Run red lights	1.89	0.07
Become angered by another road user and indicate your hostility by whatever means you can	1.86	0.06
Not using bicycle dedicated lane (when they are available)	1.84	0.07
Have skid on a wet road or manhole cover	1.83	0.05
Maneuver through vehicles	1.82	0.07
Fail to notice that pedestrians are crossing the street when you are turning	1.81	0.05
Miss yield signs and narrowly avoid colliding with traffic that has the right of way	1.80	0.06
Riding so close to the vehicle in front of you that it is hard to stop in an emergency	1.79	0.06
Drive in the opposite direction of traffic flow	1.75	0.06
Ride in fast moving traffic lanes	1.72	0.06
Have difficulty controlling your bicycle downhill	1.63	0.05
Fail to notice a pedestrian waiting to cross at a crosswalk	1.63	0.05
Do not know which gear to use	1.54	0.05
Hard to maintain balance at low speeds	1.50	0.05
Send texts while riding your bike	1.50	0.06
Do not yield to pedestrians	1.45	0.05
Attempt wheelies	1.39	0.06
Have given chase when angered by another rider or road user	1.31	0.05
Ride under the influence of alcohol or drugs	1.11	0.03

3.3. Demographic differences on the BRBQ dimensions

Table 4 presents the average scores of the riders by gender using Mann-Whitney U test. Results indicated that male riders reported more Stunts and Distractions violations than females. On the contrary, female riders reported more Control Errors than male riders. Traffic Violations, Signaling Violations, and Notice Errors were not significantly different across genders.

Kruskal Wallis Test results showed that bicycling experience failed to exert any significant influences on the BRBQ means for the Notice Failures (X^2 (31) = 39.7, p = 0.135) and Traffic Violations dimension (X^2 (31) = 30.61, p = 0.486). Yet, the analysis indicated that as riders gain more experience, the frequency of Signaling Violations increased (X^2 (31) = 53.1, p = 0.008); while their Stunts and Distraction (X^2 (31) = 47.8, p = 0.22) and Control Errors (X^2 (31) = 48.9, p = 0.022) declined.

Bicyclists' age did not show any significant influence on the Notice Failures (X^2 (3) = 6.2, p = 0.138) and Traffic Violations dimension (X^2 (3) = 2.40, p = 0.495), Signaling Violations (X^2 (3) = 5.5, p = 0.138), and Control Errors (X^2 (3) = 3.45, p = 0.327). On the other hand, as riders age increased, the Stunts and Distractions (X^2 (3) = 38.4, p = 0.000) decreased. Additionally, Kruskal Wallis Test results indicated that education failed to exert any significant influences on the BRBQ means for Signaling Violations (X^2 (5) = 4.3, p = 0.514) and Notice Failures (X^2 (5) = 9.9, p = 0.080). In contrast, as riders' education increased, the stunts and distraction dimension (X^2 (5) = 32.2, p = 0.000) as well as the Traffic Violations (X^2 (5) = 11.1, p = 0.049), and Control Errors dimension (X^2 (5) = 24.0, p = 0.000) declined.

Contexts of the riding and purpose of the trip failed to exert any significant influences on the BRBQ means for Notice Failure (context of riding: X^2 (2) = 0.46, p = 0.795; purpose of riding: X^2 (2) = 1.19 p = 0.551), Traffic Violation (context of the riding: X^2 (2) = 1.81 p = 0.404; purpose of riding: X^2 (2) = 0.72 p = 0.697), and Signaling Violations (context of riding: X^2 (2) = 3.11 p = 0.211; purpose of riding: X^2 (2) = 4.81 p = 0.090). On the other hand, riders who rode more frequently in the rural setting reported more Stunts and Distractions than bicyclists in the urban context, and less Stunts and Distractions than bicyclists in the mountainous area (X^2 (2) = 17.5, p = 0.000). Professional bicyclists also reported more Stunts and Distractions than other groups (X^2 (2) = 22.61 p = 0.000). Instead, professional bicyclist reported less Control Errors in comparison to those who mainly bicycled for recreational purposes. Respondents who rode more frequently in the rural area reported more Control Errors than those who mainly bicycled in the mountainous area and less Control Errors than bicyclists in urban context (X^2 (2) = 15.91 p = 0.000).

Table 3
Dimensions of the BRBQ.

Items	Dimensions				
	1	2	3	4	5
7. Speed up to beat the traffic light turning red	0.70				
30. Ride in prohibited expressways, drives, highways, interstate routes, bridges, and thruways unless authorized by signs	0.65				
8. Run red lights	0.64				
15. Become angered by another road user and indicate your hostility by whatever means you can	0.61				
13. Have felt frustrated by other road users	0.61				
14. Felt angry and aggressive towards another road user	0.60				
6. When riding at the same speed as other traffic, you find it difficult to stop in time when a traffic light has turned against you	0.58				
29. Not using bicycle dedicated lane (when they are available)	0.52				
27. Drive in the opposite direction of traffic flow	0.51		0.39		
28. Do not yield to pedestrians	0.49		0.37		
12. Riding so close to the vehicle in front of you that it is hard to stop in an emergency	0.43	0.35			
37. Riding without having at least one hand on handlebars at all times		0.77			
16. Talk on the phone while riding your bike		0.74			
23. Attempt wheelies		0.69			
17. Send texts while riding your bike		0.67			
10. Get involved in unofficial races with other riders or drivers		0.64			
19. Listen to music while riding		0.53			
22. Hard to maintain balance at low speeds			0.77		
26. Have difficulty controlling your bicycle downhill			0.73		
20. Do not know which gear to use			0.65		
21. Have skid on a wet road or manhole cover			0.51		
25. Almost lost control due to obstacle presence in road surface			0.50		
2. Fail to notice someone stepping out from behind a parked vehicle until it is nearly too late				0.79	
1. Fail to notice that pedestrians are crossing the street when you are turning				0.76	
3. Fail to notice a pedestrian waiting to cross at a crosswalk				0.69	
5. Been distracted or pre-occupied to the point that you did not that the vehicle in front of you slowed and you had to brake hard to avoid a collision				0.67	
4. Miss yield signs and narrowly avoid colliding with traffic that has the right of way				0.41	
32. Fail to give hand signals (at least two seconds preceding the beginning of the movement) for left and right turns					0.81
33. Fail to give appropriate signal for stopping the bicycle					0.77
34. Fail to give an audible signal when overtaking pedestrians					0.75

Table 4
Average score of males and females on BRBQ dimensions.

Dimensions	Male	Female	Z (p value)	Mann-Whitney U
Stunts and Distractions	2.02 (0.79)	1.66 (0.79)	-4.23 (0.000)	5650.5
Control Errors	1.67 (0.56)	2.00 (0.76)	-4.36 (0.000)	5560.5
Traffic Violations	1.98 (0.67)	1.90 (0.80)	-1.16 (0.248)	7665.5
Signaling Violations	2.96 (1.14)	2.74 (1.08)	-1.20 (0.229)	7634.5
Notice Failure	1.92 (0.71)	1.81 (0.82)	-1.24 (0.214)	7604.5

3.4. BRBQ dimensions and relation with multi-vehicle crashes

Table 5 presents the correlations between self-reported multi-vehicle crashes, the BRBQ dimensions, and demographic characteristics. Among the BRBQ dimensions, Stunts and Distractions (for all crashes: $r(304) = 0.19$, $p < 0.001$; for at fault crashes: $r(304) = 0.22$, $p < 0.001$) and Traffic Violations (for all crashes: $r(304) = 0.23$, $p < 0.001$; for at fault crashes: $r(304) = 0.21$, $p < 0.001$) had significant positive correlations with self-reported multi-vehicle crashes. Except for Signaling Violations which had a positive correlation with all self-reported multi-vehicle crashes ($r(304) = 0.39$, $p < 0.500$) and a negative correlation with at-fault self-reported multi-vehicle crashes ($r(304) = -0.06$, $p < 0.332$), the rest of the dimensions were positively correlated with self-reported multi-vehicle crashes. However, these correlations failed to reach significance.

Table 6 shows the results of binary logistic regression models for predicting all self-reported multi-vehicle crashes and at-fault self-reported multi-vehicle crashes. Both models included the five dimensions from the BRBQ in addition to some other exposure-oriented variables. Both models had pseudo R-square values of 0.12. Riding experience (for all crashes: $\beta = -0.02$, $p < 0.038$; for at-fault crashes: $\beta = -0.04$, $p < 0.002$), history of crashes (for all crashes: $\beta = 0.81$, $p < 0.000$; for at-fault crashes: $\beta = 0.94$, $p < 0.000$), urban context (for all crashes: $\beta = 0.58$, $p < 0.044$; for at-fault crashes: $\beta = 0.69$, $p < 0.013$) were the significant predictors of self-reported multi-vehicle crashes in both models. Riding hours per day ($\beta = 0.03$, $p < 0.050$) and Rider's age ($\beta = -0.04$, $p < 0.002$) were only significant for all self-reported multi-vehicle crashes and it failed to reach a significant level for at-fault self-reported multi-vehicle crashes. On the other hand, rural area ($\beta = 0.96$, $p < 0.006$) was only a significant predictor of at-fault

Table 5
Correlation between the BRBQ dimensions, self-reported multi-vehicle crashes, and rider's characteristics.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	**All self-reported multi-vehicle crashes**	1																	
2	**Self-reported at fault multi-vehicle crashes**	.65**	1																
3	**Traffic Violations**	.23**	.21**	1															
4	**Stunts and Distractions**	.19**	.22**	0	1														
5	**Control errors**	0.02	0.05	0	0	1													
6	**Notice Failure**	0.02	0.04	0	0	0	1												
7	**Signaling Violations**	0.04	-0.06	0	0	0	0	1											
8	**Riding hours per day**	.22**	0.09	0.03	.31**	-.15**	-0.01	.12**	1										
9	**Riding experience**	-0.03	-0.09	-0.05	-0.06	-.13*	-.14*	.13*	0.04	1									
10	**Rider's age**	-.24**	-.19**	-.12*	-.36**	0.1	-.14*	.11*	-.32**	.28**	1								
11	**Education**	-0.07	-0.01	-0.05	-.28**	.12*	-0.11	0.06	-.31**	0.1	.35**	1							
12	**Gender**	0.02	0.03	0.05	.19**	-.22**	0.06	0.08	.24**	.24**	0.01	-0.1	1						
13	**Professional Bicycling**	-0.01	-0.04	-0.02	-0.03	-0.02	-0.03	-0.06	-0.09	0.06	0.06	.19**	-0.03	1					
14	**Recreational Purpose**	-0.01	0.01	-0.01	-0.12*	-0.02	-0.08	-0.14*	-0.18**	0.07	0.21**	0.23**	-0.02	-0.52*	1				
15	**Other Purposes**	-0.11**	-0.11**	-0.05	-0.14**	0.14**	0.02	0.11**	-0.13**	-0.00	0.12**	0.10*	-0.06	-0.25**	-0.69**	1			
16	**Urban Context**	0.16**	0.17**	0.09*	0.23**	-0.12**	0.00	0.11**	0.24**	0.10**	-0.07	-0.07	0.26**	0.15**	0.08*	-0.23**	1**		
17	**Rural Context**	-0.22**	-0.28**	-0.08*	-0.17**	0.05	0.00	-0.056	-0.15**	-0.054	0.08*	0.04	-0.18**	-0.05	-0.11**	0.17**	0.63**	1	
18	**Mountainous Context**	0.01	0.05	-0.04	-0.14**	0.09*	-0.011	-0.092*	-0.17**	-0.09*	0.00	0.05	-0.17**	-0.15**	0.00	0.11**	0.65**	0.16**	1

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Table 6
Predictors of self-reported multi-vehicle crash (1 = reported crash; 0 = otherwise) and self-reported multi-vehicle at-fault crash (1 = reported crashes; 0 = otherwise).

	All self-reported multi-vehicle crash		Self-reported multi-vehicle at-fault crash	
Variable	Coef.	Std. Err.	Coef.	Std. Err.
Dimension 1) Traffic Violations	0.68**	0.169	0.595**	0.164
Dimension 2) Stunts and Distractions Violations	0.042	0.151	0.230*	0.117
Dimension 3) Control Errors	0.445*	0.177	0.132	0.176
Dimension 4) Notice Failures	0.708**	0.162	-0.217	0.158
Dimension 5) Signaling Violations	-0.021	0.085	-0.267**	0.094
Riding Experiences	-0.022*	0.011	-0.037**	0.012
Riding Hours Per Day	0.026*	0.013	0.007	0.015
History of Crashes	0.813**	0.193	0.937**	0.199
Riders` Age	-0.036**	0.011	-0.016	0.012
Education Level	0.092	0.075	0.199*	0.081
Gender (1 = Male)	0.221	0.232	0.124	0.239
Professional Bicyclist	0.153	0.344	0.366	0.351
Recreational Purpose	0.138	0.214	-0.072	0.227
Urban Context	0.576*	0.286	0.689*	0.278
Rural Context	0.387	0.344	0.956**	0.346
Constant	0.265	0.713	-1.061	0.742

* < 0.05
** < .01

self-reported crashes. More importantly, in both multi-vehicle crash states, the Traffic Violations dimension (for all crashes: $\beta = 0.68$, $p < 0.000$; for at-fault crashes: $\beta = 0.60$, $p < 0.000$) was the predictor of self-reported multi-vehicle crashes. The Notice Failures dimension ($\beta = 0.71$, $p < 0.000$) and Control Errors dimension ($\beta = 0.45$, $p < 0.019$) were significant predictors of all self-reported multi-vehicle crashes. On the other hand, Stunts and Distractions dimension ($\beta = 0.15$, $p < 0.050$) and Signaling Violations dimension ($\beta = -0.27$, $p < 0.004$) were significant predictors of at-fault self-reported multi-vehicle crashes.

4. Discussion

Based on the Reason et al. (1990) taxonomy of human error, we developed a 34-item Bicycle Rider Behavior Questionnaire and tested it on a sample of 306 bicyclists, convenience-sampled from within an active bicycling network. From the data, we identified a behavioral five-dimension solution to the BRBQ – each with good internal reliability ranging from 0.70 to 0.84. The distinction between intentional violations (i.e., Stunts and Distractions, Traffic Violations and Signaling Violations) and unintentional errors (i.e. Attention Errors and Control Errors) is consistent with the original theoretical taxonomy of human errors.

The first dimension included behaviors that according to Iranian traffic rules, were categorized as Traffic Violations. One possible explanation why bicyclists conduct these violations is to gain an advantage in various traffic situations (e.g., reduce their waiting time for the traffic light). Aggressive violations behaviors were also loaded in this dimension. Other road users' behavior towards bicyclists and the lack of high-quality facilities could explain bicyclists' aggressive violations. This dimension corresponds with the ordinary and aggressive violations in the DBQ, which has been identified in several studies (e.g., Lawton et al., 1997).

The Stunts and Distractions dimension included intentional riders' behaviors that have the potential to endanger other road users' safety. One explanation could be that riders perform these behaviors as acts of sensation seeking (i.e., stunts) or mental distractions (e.g., listening to music), which could help them to facilitate their performances (Laukka and Quick, 2013). In the third dimension, three items loaded related to noticing other road users. These behaviors reflect that bicyclists are sometimes unaware of the presence of other road users, particularly pedestrians; this dimension is similar to the error dimension in the DBQ (e.g., Davey et al., 2007).

Skill-related items loaded on the Control Errors dimension (e.g., difficulty of maintaining balance at low speeds). Elliott et al. (2007), focusing on motorcycles, labeled similar items as non-intentional and argued that some of them might be as related to carelessness, inattentive riding style, or excessive speed, as they are with lack of skill and appropriate human control (e.g., hard to control bicycle on a downhill grade). The emergence of the control error dimension is broadly consistent with errors due to inexperience (e.g., Aberg and Rimmo, 1998) and Control Errors (e.g., Elliott et al., 2007) dimensions in previous studies.

Unlike motorized vehicles, bicycles are not equipped with signaling devices (i.e., horns, turn indicators, and brake lights). The Signaling Violations dimension included behaviors that bicyclists need to perform to notify other road users about change in their speed or direction, most often using hand-signals or other cues. Signaling to other road users increases riders' workload, and this load is cognitively more resource demanding among elderly and in complex traffic situations (Vlakveld et al., 2015). Several studies showed that both riders and drivers tend to compensate and reduce their speed as their mental workload increases (e.g., Fuller, 2005; Vlakveld et al., 2015). However, bicycle riders need to maintain a minimum speed to maintain their balance. Likewise, having two hands on the handlebar helps riders to maintain the balance of the bicycle. Leaving one hand free for signaling concurrent with reduction in speed could increase the likelihood of Control Errors. This situation may worsen particularly in complex traffic situations (e.g., hand-signaling in slow and congested traffic in urban area). The relation between bicyclists' workload in complex traffic situation, control errors, and signaling need to be investigated. Nevertheless, future technologies could be integrated to reduce the workload on bicyclists (e.g., connected vehicles). Equipping bicycles with communication equipment, equivalent to other vehicles in the road system (e.g., indicators), could increase bicyclists' safety.

Gender comparisons indicated that females were more prone to Control Errors; on the other hand, males reported more intentional Traffic Violations. As riders age and their riding experience increased, the frequency of reported aberrant behaviors declined, whereas their Control Errors increased. These behavioral differences by gender, age, and riding experience were in line with several studies focusing on the DBQ (e.g., Aberg and Rimmo, 1998; Blockey and Hartley, 1995).

Unsurprisingly, all the dimensions (except Signaling Violations predicting at-fault self-reported multi-vehicle crash) had positive correlations with self-reported multi-vehicle crashes. Moreover, violations were significant predictors of self-reported at-fault multi-vehicle crashes. Notice Failures and Traffic Violations predicted all types of self-reported multi-vehicle crashes. Road safety countermeasures which target violations and reduce bicyclists' errors could also reduce the crash risk among bicyclists. Further, studies could be conducted to identify the underlying motivation of bicyclists' violations and interventions targeting these motivational factors may be developed.

Considering the relation between riding context (i.e., urban, and rural context), dimensions of the aberrant behaviors, and self-reported crashes, we conclude that bicyclists and policy makers should develop behavioral norms and supportive infrastructure and regulatory systems that discourage aberrant behavior and increasing expectancy and predictability of other road users. Developing infrastructure, policy, and education programs that self-enforce against unsafe behavior will help bicyclists to reduce their crash risk.

5. Limitations of the study

This study aimed to develop a bicycle-oriented behavioral questionnaire that follows a similar methodological approach as the motorcycle (MRBQ) and car driver (DBQ) instruments. We developed the BRBQ and tested it against a limited sample of bicyclists. It is also worthy to notice that the power of the study would benefit in a larger sample. The results here, particularly the regression results, represent the experiences of that sample, and not the larger bicycling population in Iran or the world. Indeed, the BRBQ can be applied to any subset of the bicycling community, and the results will likely differ. This study is limited to the development of the instrument and the limited application.

A fundamental limitation of this and other self-reported behavioral questionnaires is that self-report instruments are often vulnerable to socially desirable responses. However, Lajunen and Summala (2003) reported that social desirability has a relatively low impact on self-reported responses to aberrant behaviors. In addition, providing a context where the respondents could not be singled out could reduce the negative effect of social desirability. In this study, a setting (i.e., an anonymous online survey) was provided for respondents to minimize the negative effect of the social desirability. Likewise, individuals may have forgotten or underreported their crashes over the time (Maycock et al., 1991). A three-year period was used in this study to reduce the probability of memory bias but could result in underreporting crashes, particularly minor ones. While recognizing that police fault assignment is imperfect, we aimed to include this criterion to reduce subjectivity from the respondent perception of fault. In Iran, the fault is generally assigned by the responding officer to the road user with the highest contribution of fault in the crash, regardless of mode. While fault is generally assigned to one road user, there are likely many contributing crash factors and user behaviors. One approach, in the future, would also be to ask the respondents if their perceived contribution to the crash is consistent with the police assignment of fault.

One of the most common types of bicycle crashes is single-bicycle crashes. During the pilot and focus group studies, the authors learned that the participants did not have a unified definition of a single-bicycle crash. One challenge in reporting single-bicycle crashes was the lack of a clear-cut threshold for considering an incident as a single-bicycle crash. Some riders recalled their Control Errors as a single-bicycle crash, whereas others only reported an incident as a single-bicycle crash when the outcome was severe. Consequently, single-bicycle crashes were removed from the study to reduce the complexity and only include crashes that involved at least two road users. A future methodological improvement would be to introduce a common definition of a single-bicycle crash (e.g., falling from the bike or dropping your bike, even if landing on your feet).

6. Conclusion

This study reports a new measurement instrument of aberrant bicycling behavior with feasible psychometric properties, which is well-suited to evaluate aberrant riding behaviors of bicyclists in a high-risk context. A five-dimension solution with acceptable internal consistency for the BRBQ was confirmed in a sample of bicyclists. Regarding the discriminant validity, internal reliability of the dimensions, and relation with self-reported multi-vehicle crashes, one can conclude that this study was successful in developing a tool that could be useful for measuring the aberrant behavior of the bicyclists. The findings presented a sample of Iranian bicyclists and results cannot be transferred from this setting to others. The BRBQ instrument needs further validation in other settings.

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