Journal of Transport Geography 114 (2024) 103754

Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

Yes, size does matter (for cycling safety)! Comparing behavioral and safety outcomes in S, M, L, and XL cities from 18 countries

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A R T I C L E I N F O

Keywords:
Urban cycling
City size
Riding behavior
Cycling crashes
Safety outcomes

A B S T R A C T

Although most actions aimed at promoting the use of active transport means have been conducted in 'large' cities, recent studies suggest that their cycling dynamics could hinder the efforts put into infrastructural, modal share, and cycling culture improvements.

Aim: The present study aimed to assess the role of city sizes on riding behavioral and crash-related cycling outcomes in an extensive sample of urban bicycle users.

Methods: For this purpose, a full sample of 5705 cyclists from >300 cities in 18 countries responded to the Cycling Behavior Questionnaire (CBQ), one of the most widely used behavioral questionnaires to assess risky and positive riding behaviors. Following objective criteria, data were grouped according to small cities (S; population

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https://doi.org/10.1016/j.jtrangeo.2023.103754
Received 21 May 2023; Received in revised form 12 November 2023; Accepted 14 November 2023
Available online 5 December 2023

of 50,000 or fewer), medium cities (M; population between 50,000 and 200,000), large cities (L; population between 200,000 and one million), and megacities (XL; population larger than one million).
Results: Descriptive analyses endorsed the associations between city size, cycling behavioral patterns, and mid-term self-reported crash outcomes. Also, it was observed a significant effect of the city size on cyclists' traffic violations and errors (all $p < .001$). However, no significant effects of the city size on positive behaviors were found. Also, it stands out that cyclists from megacities self-reported significantly more violations and errors than any of the other groups. Further, the outcomes of this study suggest that city sizes account for cycling safety outcomes through statistical associations, differences, and confirmatory predictive relationships through the mediation of risky cycling behavioral patterns.
Conclusion: The results of the present study highlight the need for authorities to promote road safety education and awareness plans aimed at cyclists in larger cities. Furthermore, path analysis suggests that "size does matter", and it statistically accounts for cycling crashes, but only through the mediation of riders' risky behaviors.

1. Introduction

While cycling and walking remain the most promoted active means of transport due to their sustainable, inexpensive, and health-related features, some studies have suggested that these benefits might vary considerably alongside infrastructural factors. Indeed, it is common nowadays to find references to urban environments closely linked to transportation development under both environmental and human-based approaches (Brüchert et al., 2022; Mertens et al., 2017; Winters et al., 2010). In other words, road environmental dynamics, behavioral patterns, and safety outcomes might significantly differ based on typical factors that distinguish cities, such as their size and modal share patterns (Gao et al., 2018; Useche et al., 2022a, 2022b; Winters et al., 2010). Therefore, it remains relevant to generate scientific knowledge on the safety and behavioral traits of cyclists according to the size of the city in which they commonly ride.

Regarding cycling safety, the behavior of cyclists is a major factor that can even modulate their crash likelihood (Alavi et al., 2017; O'Hern et al., 2021; Useche et al., 2018a; Useche et al., 2019a; Wang et al., 2020; Zheng et al., 2019). At a methodological level, self-reported road behaviors are predominantly measured through behavioral questionnaires (Granié et al., 2013; Hezaveh et al., 2018; Reason et al., 1990), among which the Cycling Behavior Questionnaire (CBQ) has proven to be taxonomically accurate and psychometrically useful.

In practical terms, it assesses self-reported cycling behavior by targeting risky deliberate (i.e., traffic violations), risky non-deliberate (i.e., errors), and positive cycling behaviors. The CBQ is also sensitive to age and gender-based differences (Useche et al., 2018b; Useche et al., 2019a; Useche et al., 2019b; Useche et al., 2021a,b; Useche et al., 2022a; Useche et al., 2022b), and it has shown correlations between risk perception, psychological distress, road distractions, and traffic-rule knowledge (Useche et al., 2018c; Useche et al., 2019a, 2019b).

Moreover, another strength of this self-report method to assess cycling behaviors has been its statistical consistency when crossed with theoretically related third variables. For instance, the CBQ has been dimensionally correlated with other psychosocial issues, such as cycling anger, sensation seeking, impulsiveness, and defiance of norms in previous studies (Zheng et al., 2019). However, to the best of our knowledge, no previous research has analyzed the potential effect that the city size may have on the results of this questionnaire. Therefore, the question arises: "Can *self-reported cycling behaviors and crashes be conditioned by the size of the city in which they ride?*"

1.1. City size and cycling behavior: some key evidences

Traditionally, studies covering cycling behaviors have mostly been conducted in one city or one country (Brüchert et al., 2022; Gao et al., 2018; Winters et al., 2010, 2018; Zhang et al., 2022). To overcome this limitation, a study covering different city sizes around the world could provide the scientific body of knowledge with more insight into the interplay of city/town size, cycling behaviors, and crash-related outcomes (Gao et al., 2018).

In this regard, a recent longitudinal study analyzed cyclist crash rates and risk factors in seven European cities, representing a range of environments in terms of size, population characteristics, mode shares, built environments, and culture (Branion-Calles et al., 2020). These authors observed differences in crash rates between cities, neighborhoods, and population groups, and concluded that future research should focus on representative datasets that can integrate the most policy-relevant crash risk factors (Branion-Calles et al., 2020). With these results in mind, a study covering a larger set of cities may shed some light on the potential behavioral differences between cyclists from cities of different sizes. To the best of our knowledge, no previous research has conducted self-reported behavioral analysis, such as that included in the CBQ, in a large set of cities from all around the world.

Bearing in mind the aforementioned, the core aim of this study was to compare the self-reported risky and protective cycling behaviors and crashes among cyclists riding in cities of different sizes. A second aim was to study the association between deliberate and non-deliberate risky cycling behaviors according to the city size. Based on the theoretical assumptions presented in the literature review, we hypothesized that cyclists riding in larger cities would present more negative results in terms of the aforementioned phenomena. Rather than a direct effect, we hypothesized that the effect of city size on cyclists' crash-related outcomes is mediated by their self-reported riding behaviors.

2. Methods

2.1. Study design

This cross-sectional and questionnaire-based study (Ethical IRB: HE0002170921) compared the outcomes of different questionnaires on cycling behavioral issues among bicycle riders from small (S), medium (M), and large (L) cities, and megacities (XL). As there is not a fixed consensus on this typology, the city classification chosen for this study was based on both the guidelines advised by the Organization for Economic Co-operation and Development (OECD, 2022) and previous research with bicycle users (see Brüchert et al., 2022; Gao et al., 2018; Winters et al., 2018).

The splitting criteria were defined as follows: cities were considered 'small' if they had a population of fewer than or equal to 50,000 inhabitants; 'medium' if their population ranged between 50,000 and 200,000 people; 'large' cities when their population ranged between 200,000 and one million; and 'megacities' if the number of inhabitants was larger than one million. Regarding the individual city size figures, the OECD's inhabitant database, version 2021 (OECD, 2021), was used. Also, in very few exceptional cases (< 2%), in which some municipality sizes (especially in the case of very small ones) were not determined in the OECD database, third-party web sources (e.g., citypopulation.de; city-facts.com) were accessed to double-check this data.

As for sample size calculation, a priori power analysis (G*Power 3.0; Faul et al., 2007) was conducted. It showed an initial minimum sample size of approximately $n = 1424$ individuals, if an effect size (f) of 0.11, a power (1-ß) of 0.95, and a maximum margin of error/confidence interval (CI) of 5% are assumed. However, bearing in mind the potential population heterogeneity, which suggested the need for collecting greater amounts of data, and its beneficial effect of decreasing the margin of error, the number of surveys was higher, enhanced by the relatively elevated response rate (estimated at 60–70%). Moreover, once the data had been collected, the subsequent post hoc statistical power analysis endorsed the assumption that an optimum statistical power had been achieved.

2.2. Participants

The full study sample was composed of $n = 5705$ urban cyclists (51.2% female) from >350 urban locations in 18 countries (4 continents) around the world. A graphical overview of the cities covered by this study is presented in Fig. 1. Groups were balanced in terms of gender and age (which ranged from 18 to 80). Descriptive socio-demographic data and basic bicycle journey features of the sample are presented in Table 1.

2.3. Description of the questionnaire

Participants answered an online-based questionnaire structured into two core sections. The first addressed socio-demographic features (i.e., age, gender, country and city of origin, educational level, occupation) and basic cycling information (frequency, trip length, motives). The second section aimed at assessing behavioral and safety-related cycling outcomes from a self-report approach. The Cycling Behavior Questionnaire (CBQ; See Appendix 1) is a Likert-type research form composed of 29 questions related to both risky and protective riding behaviors (see Useche et al. [2022a] and McIlroy et al. [2022] for further information). Its dimensional structure, composed of three core factors, aims to allow cyclists to self-report their cycling behaviors according to three categories: deliberate risky behaviors (traffic violations; 8 items; Cronbach's alpha [α] = 0.777/ McDonald's omega [ω] = 0.779), non-deliberate risky behaviors (riding errors; 15 items; α = 0.920/ω = 0.932), and protective/positive behaviors (6 items; α = 0.798/ω = 0.801).

This questionnaire was applied using a self-report methodology in its validated language versions (i.e., Chinese [Zheng et al., 2019], Dutch and French [Useche et al., 2021c], English [O'Hern et al., 2021], and Spanish [Useche et al., 2018d]). Additionally, further versions in German, Portuguese, Danish, Finnish, Malay, Polish, Russian, and Slovak were also used to cover the countries appended in the study composing its recent cross-cultural validation (Useche et al., 2022a). Concerning the specific application of the questionnaire, it evaluated the riding behaviors (risky and protective) on a frequency-based Likert scale with five levels (0 never; 1 = hardly ever; 2 = sometimes; 3 = frequently; 4 = almost always) through the basic instruction: "Estimate how often you do the following when cycling". Finally, a supplementary question inquired about the crashes suffered by participants during the previous five years, regardless of their severity. This was uniformly used as a self-reported cycling crash indicator.

2.4. Data analysis

After a careful coding process, the database was curated, and study variables were scored in accordance with the directions provided by the authors of each scale/instrument applied. After applying a (Log10-based) logarithmic transformation to statistically correct continuous variables, participants were organized into four groups, depending on the size of their city/town. In a first analysis step and given the ordinal nature of some of the study variables, the association between city sizes and the self-reported frequency of deliberate and non-deliberate risky cycling behaviors was assessed through partial correlations. For these correlations, cyclists' gender was included to avoid biases due to the typical behavioral differences between male and female riders described in comparative literature (Useche et al., 2018c).

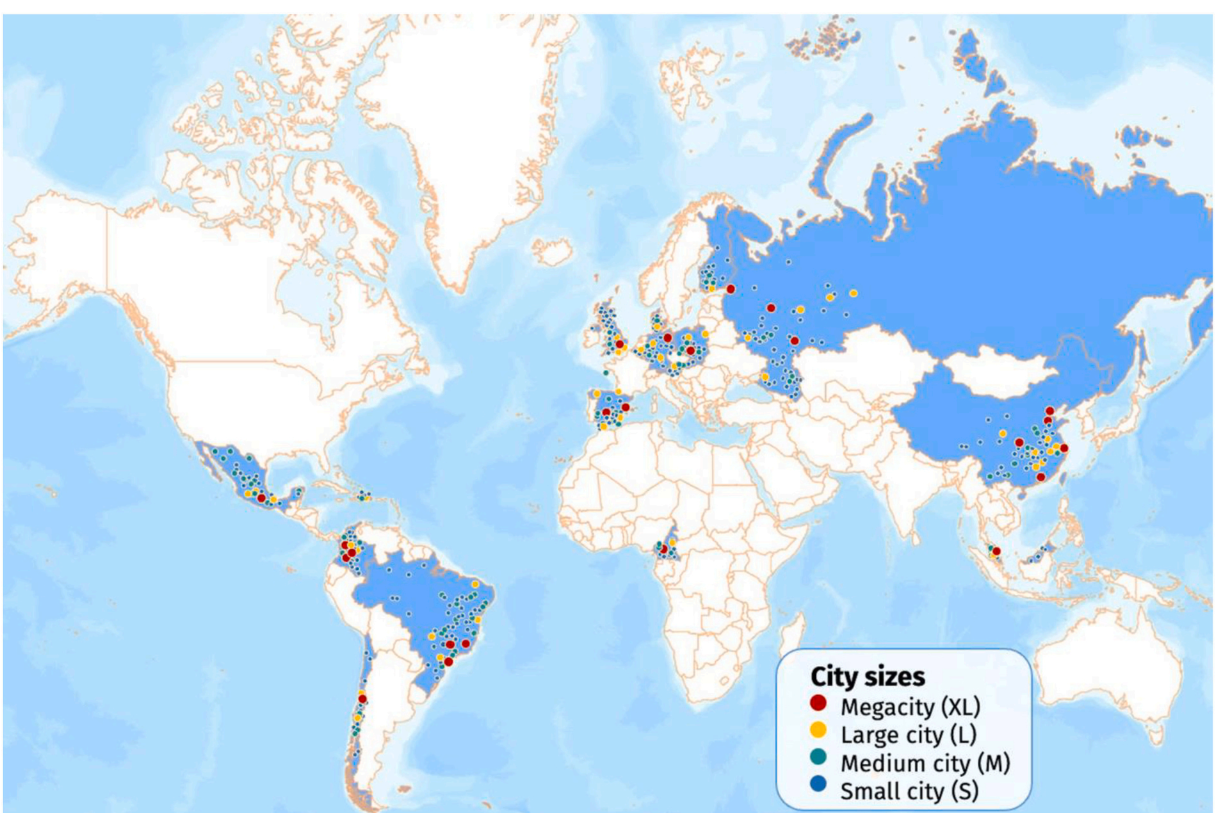

Fig. 1. Study coverage: graphical representation of the countries and cities covered by the study.

Table 1
Socio-demographic and riding characteristics of the sample according to city size (OECD-based criteria).

Feature	Category	Fewer than 50,000	50,000 to 200,000	200,000 to 1 million	>1 million	Total
	Female	51.2	44.7	39.4	30.9	39.7
Gender	Male	48.5	54.7	59.2	68.6	59.6
	Other	0.3	0.6	1.4	0.6	0.7
	Student	36.8	39.1	32.1	35.5	35.4
	Employed	44.7	43.6	48.0	40.4	44.0
	Self-employed	7.7	8.2	9.4	14.8	10.7
Occupation	Unemployed	1.0	2.2	3.3	4.5	3.1
	Retired	5.5	3.8	2.9	2.1	3.3
	Homemaker	0.8	0.7	1.3	0.9	0.9
	Other	3.4	2.5	3.0	1.7	2.5
	Primary or lower	5.5	2.5	1.3	1.4	2.4
Education	Secondary/ high school	18.5	17.5	15.2	13.8	15.8
	Technical/intermediate training	17.7	11.4	10.8	23.6	16.7
	Undergraduate degree	40.2	43.1	48.7	38.9	42.7

Variable	City-size group		N	M	SD	95% CI	
						Lower	Upper
Age (years)	1	S - Small cities	1100	35.75	15.10	34.86	36.64
	2	M - Medium cities	1016	34.54	14.76	33.63	35.45
	3	L - Large cities	1622	35.13	13.91	34.45	35.80
	4	XL - Megacities	1967	31.21	11.07	30.72	31.70
	Total		5705	33.79	13.55	33.44	34.14
Weekly cycling hours	1	S - Small cities	1100	4.78	4.94	4.48	5.07
	2	M - Medium cities	1016	5.01	4.88	4.72	5.32
	3	L - Large cities	1622	5.80	5.89	5.50	6.08
	4	XL - Megacities	1967	5.62	5.83	5.36	5.88
	Total		5705	5.40	5.54	5.26	5.54
Typical journey length (minutes)	1	S - Small cities	1100	49.42	40.50	47.12	51.96
	2	M - Medium cities	1016	45.98	41.93	43.50	48.72
	3	L - Large cities	1622	47.12	41.36	45.18	49.23
	4	XL - Megacities	1967	44.10	35.75	42.66	45.87
	Total		5705	46.33	39.50	45.42	47.49

Notes: [a]SD = Standard Deviation; [b]CI = Confidence Interval (at the level 95%); OECD criteria small cities [S population < 50,000], medium cities [M population between 50,000 and 200,000], large cities [L population between 200,000 and 1,000,000], and megacities [XL population > 1,000,000].

As for inter-group comparisons, a one-way analysis of variance (ANOVA) was conducted in order to test potential differences in terms of different cycling outcomes among the four city sizes included in this study. Effect sizes (ES) were evaluated with eta partial squared (ηp^2), where $0.01 < \eta p^2 < 0.06$ constitutes a small effect, $0.06 \le \eta p^2 \le 0.14$ constitutes a medium effect, and $\eta p^2 > 0.14$ constitutes a large effect. The post hoc testing for the age group was applied using the Bonferroni adjustment. The effect size (ES) was calculated as Cohen's d with Hedges corrections (Lakens, 2013). This value is reported as unbiased Cohen's d (dunb; Cumming, 2014), with dunb <0.50 constituting a small effect, 0.50 ≤ dunb ≤0.79 moderate, and dunb ≥0.80 a large effect (Cohen, 1988).

Finally, the confirmatory associations between city size and (*i*) traffic violations; (*ii*) riding errors; and (*iii*) self-reported crashes of cyclists were assessed through path analysis, controlling for basic confounders (i.e., age and cycling exposure). This type of test, understood in specialized literature as a subset of structural equation modeling procedures, constitutes a useful method to determine and differentially assess the effects of a set of variables acting on a specified outcome via multiple causal (but theoretically-based) confirmatory pathways (Streiner, 2005).

All the analysis was performed with IBM® Statistical Package for Social Sciences (SPSS, version 28; IBM Corp., Armonk, NY, US), except for the path analysis, which was carried out with IBM SPSS AMOS, version 28.0.

3. Results

3.1. City size in relation to cycling behaviors and safety outcomes

The initial descriptive analysis of the relationships between study variables (i.e., bivariate correlation coefficients) showed significant correlations between city size (ordinalized factor) and the whole set of continuous variables appended in the study. More specifically, city size positively correlated with self-reported cycling weekly hours ($r = 0.048$, $p < .001$), traffic violations ($r = 0.123$, $p < .001$), cycling errors ($r = 0.119$, $p < .001$), and cycling crashes ($r = 0.031$, $p = .020$). On the other hand, a negative correlation suggests that the bigger the city size, the shorter the 'most typical' cycling trip ($r = -0.064$, $p < .001$) and the less self-reported cycling-positive behaviors ($r = -0.024$, $p < .070$), despite having a considerably low magnitude. Additionally, cycling weekly hours positively correlated with violations ($r = 0.310$, $p < .001$), errors ($r = 0.124$, $p < .001$), errors ($r = 0.026$, $p = .050$), positive behaviors ($r = 0.047$, $p < .001$), and crashes ($r = 0.190$, $p < .001$). Typical trip length was not correlated with cycling violations ($r = -0.13$, $p = .336$), but it was negatively correlated with errors ($r = -0.045$, $p < .001$). Furthermore, typical trip length was positively correlated with positive behaviors ($r = 0.147$, $p < .001$) and crashes ($r = 0.077$, $p < .001$). The full set of correlations is available in Table 2.

Also, correlational facts previously endorsed by cycling safety literature stand out, such as the highly consistent correlation between self-reported violations with both riding errors ($r = 0.674$, $p < .001$) and cycling crashes ($r = 0.275$, $p < .001$). Furthermore, the relationship between violations and positive behaviors remains negative and significant ($r = -0.229$, $p < .001$). In contrast to the case of traffic violations, the more self-reported positive behaviors there were, the fewer crashes

Table 2
Partial correlations between the study variables with gender as a control variable.

	Variable	2	3	4	5	6	7
1	City size[a]	0.048**	−0.064**	0.123**	0.119**	−0.024	0.031*
2	Cycling weekly hours	1	0.310**	0.124**	0.026*	0.047**	0.190**
3	Typical trip length		1	−0.013	−0.045**	0.147**	0.077**
4	Traffic violations			1	0.674**	−0.229**	0.275**
5	Riding errors				1	−0.213**	0.273**
6	Positive behaviors					1	−0.133**
7	Cycling crashes (last 5 years)						1

Notes: [a]Ordinal variable; **The correlation is statistically significant at the level $p < .001$, **The correlation is statistically significant at the level $p < .050$.

were reported by the study participants ($r = -0.133$, $p < .001$).

3.2. Between-groups and among-groups (Post Hoc) comparisons

Comparative analysis has shown a set of significant effects of the city size on risky behavioral and safety-related outcomes, namely on cycling violations ($F_{[35701]} = 40.14$, $p < .001$, $\eta p^2 = 0.021$), errors ($F_{[35701]} = 37.85$, $p < .001$, $\eta p^2 = 0.020$), and cycling crashes ($F_{[35701]} = 5.69$, $p < .001$, $\eta p^2 = 0.003$). No significant effects of the city size on the positive behaviors were highlighted ($F_{[35701]} = 2.33$, $p = .072$, $\eta p^2 = 0.001$). Descriptive statistics and post-hoc analysis can be found in Tables 3 and 4, respectively.

After conducting the aforementioned descriptive comparisons, a set of Post Hoc (Bonferroni-adjusted) analyses was conducted, with the aim of highlighting specific differences between pairs of city sizes. Overall, the analysis outcomes (fully available in Table 4) show consistent differences between low-sized cities and their high-size counterparts, being in all (significant) cases the mean differences of a negative and significant character.

Comparative analyses helped depict key city-size-based differences, especially among small and large areas, for which differences were of a greater magnitude. In other words, cyclists from bigger urban areas self-report comparatively increased rates of traffic violations, riding errors, and cycling crashes. On the other hand, no particular significant differences between specific categorical levels (i.e., city sizes) were found for positive behaviors. A further visual analysis of these Post Hoc-based outcomes allowed us to get further insights into these trends, finding visually insightful comparative differences. The full set of graphical distributions for each dependent variable is available in Fig. 2.

It is also worth highlighting that the bigger the city, the more the distribution was tailed in the direction of more violations and errors, especially in cities with a population of more than one million. In particular, the distributions of positive cycling behaviors and crashes were the most similar or 'uniform' among the different four city size-based groups used in this study.

3.3. Association between deliberate and non-deliberate risky behaviors

Bearing in mind both the theoretical considerations appended in the literature review, as well as the significant correlation found between deliberate (i.e., violations) and non-deliberate (i.e., errors) risky behaviors in the general sample (see Table 2), the potential effect of city size in this statistical relationship was also evaluated following a multi-group approach. As shown in Fig. 3 (graphical correlations), significant correlations ($p < .001$) between violations and errors were observed in all the study groups, i.e., regardless of city sizes, even though the magnitude and consistency of such bivariate associations tended to strengthen in greater urban areas. Moreover, the city size-based group presenting the highest correlation coefficient ($r = 0.752$) were riders in cities with a population between 200,000 and 1,000,000.

3.4. Path analysis

To test the directional hypothesis on the effect of city size on both risky cycling behaviors and riding crashes, a theoretically based path model controlling for age and exposure variables was tested. The model

Table 3
Behavioral questionnaire factor scores for city population group-based comparisons.

Variable	Gr	City size	N	M	MeanDiff.[a]	SD[b]	95% CI	
							Lower	Upper
Traffic violations	1	Small	1100	0.56	2,3,4	0.51	0.53	0.60
	2	Medium	1016	0.68	1,4	0.59	0.65	0.72
	3	Large	1622	0.71	1,4	0.66	0.68	0.74
	4	Megacity	1967	0.81	1,2,3	0.63	0.78	0.84
	Total		5705	0.71		0.61	0.70	0.73
Riding errors	1	Small	1100	0.41	2,3,4	0.48	0.38	0.44
	2	Medium	1016	0.47	1,4	0.55	0.44	0.51
	3	Large	1622	0.49	1,4	0.63	0.46	0.52
	4	Megacity	1967	0.62	1,2,3	0.57	0.60	0.65
	Total		5705	0.52		0.57	0.50	0.53
Positive behaviors	1	Small	1100	3.04		0.83	2.99	3.09
	2	Medium	1016	3.00		0.86	2.95	3.06
	3	Large	1622	2.99		0.83	2.95	3.03
	4	Megacity	1967	2.96		0.82	2.92	2.99
	Total		5705	2.99		0.83	2.97	3.01
Cycling crashes	1	Small	1100	0.65	3,4	1.29	0.58	0.73
	2	Medium	1016	0.70		1.21	0.63	0.77
	3	Large	1622	0.83	1	1.43	0.76	0.90
	4	Megacity	1967	0.81	1	1.28	0.75	0.86
	Total		5705	0.77		1.31	0.73	0.80

Notes: [1,2,3,4]: Statistically significant differences with groups [1,2,3,] or [4], respectively; Gr.: Groups being compared; [a]Mean Diff. = Mean differences between groups; [b]SD = Standard deviation of the mean; CI: Confidence interval; CBQ: Cycling Behavior Questionnaire; OECD criteria = small cities [S population < 50,000], medium cities [M population between 50,000 and 200,000], large cities [L population between 200,000 and 1,000,000], and megacities [XL population > 1,000,000].

Table 4
Outcomes of Post Hoc (Bonferroni-adjusted) tests for specific city population group comparisons. Groups: (1) small city (2) medium city, (3) large city, (4) megacity.

Variable	Groups compared	Mean Diff.[a]	SE[b]	Sig.	ES (Cohen's *d*)
Traffic violations	**1–2**	−0.12	0.03	***	0.218
	1–3	−0.15	0.02	***	0.248
	1–4	−0.25	0.02	***	0.424
	2–3	−0.03	0.02	0.627	0.047
	2–4	−0.13	0.02	***	0.211
	3–4	−0.10	0.02	***	0.147
Riding errors	**1–2**	−0.06	0.03	*	0.117
	1–3	−0.08	0.02	**	0.139
	1–4	−0.21	0.02	***	0.389
	2–3	−0.01	0.02	0.924	0.033
	2–4	−0.15	0.02	***	0.277
	3–4	−0.13	0.02	***	0.217
Positive behaviors	**1–2**	0.03	0.04	0.794	0.047
	1–3	0.05	0.03	0.429	0.060
	1–4	0.08	0.03	0.050	0.097
	2–3	0.02	0.03	0.964	0.012
	2–4	0.05	0.03	0.456	0.048
	3–4	0.03	0.03	0.676	0.036
Cycling crashes	**1–2**	−0.05	0.06	0.837	0.040
	1–3	−0.18	0.05	**	0.131
	1–4	−0.15	0.05	**	0.125
	2–3	−0.14	0.05	0.051	0.096
	2–4	−0.11	0.05	0.155	0.088
	3–4	0.03	0.04	0.919	0.015

Notes: [a]Mean Diff. = Mean Difference; [b]SE = Standard Error; [c]ES = Effect Size; *The difference is significant at the level $p < .050$; **The difference is significant at the level $p < .010$; ***The difference is significant at the level $p < .001$.

development comprised two sequential steps. In step one, the model was drawn to assess the direct effects of city size on both risky riding behaviors (i.e., errors and violations) and self-reported cycling crashes. In the second step, two paths were added from both risky behavioral types to self-reported cycling crashes. The resulting model fit statistics were $x^2 = 195.167$, $p < .001$; NFI = 0.981; RFI = 0.903; CFI =0.981; TLI = 0.906; IFI = 0.981; RMSEA = 0.074, 90% CI [0.062–0.087].

The model was retained because of its theoretical plausibility and adequate fit indexes. However, as aforementioned in the data analysis section, statistical corrections (i.e., bootstrapping procedures) were applied to prevent biased results and type I errors on path significance. The path model and its standardized and bias-corrected parameter estimates are presented in Table 5 (detailed coefficients), as well as graphically in Fig. 4. The solid lines or arrows indicate significant predictive relationships between variables.

The retained path model shows four direct and significant effects of the five paths drawn. Two of these paths coming from city size are significant (and positive): city size ➔ traffic violations, and city size ➔ riding errors. However, there is not a direct path or significant association between city size ➔ cycling crashes suffered over a period of five years. On the other hand, the two behaviorally-based theoretical paths (i.e., traffic violations ➔ cycling crashes, and riding errors ➔ cycling crashes) were both significant and positively explained the endogenous variable. This suggests that the relationship between city size and self-reported cycling crashes may be mediated by users' behavioral characteristics. The full set of paths, bias-corrected coefficients, and significance levels are graphically shown in Fig. 4.

4. Discussion

The present study assessed the role of city sizes on riding behavioral and crash-related cycling outcomes in an extensive sample of urban bicycle users. In this regard, it was initially hypothesized that these outcomes may largely differ, given that key literature-based issues suggest that larger cities can pose 'additional' threats to active transport users (Goel, 2023; Winters et al., 2018). Overall, and in accordance with the study hypothesis, the core findings of this research suggest that city sizes may play a critical role in both behavioral and safety-related outcomes of urban bicycle riders.

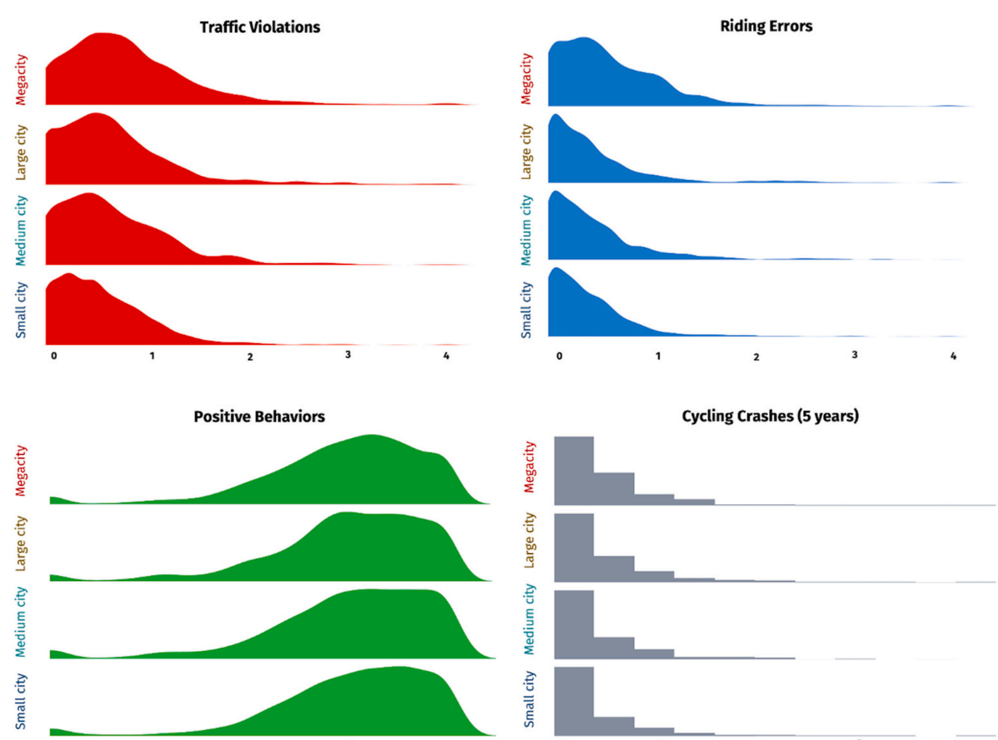

Fig. 2. Cycling behavioral variables' density charts. Density charts of the three dimensions of the Cycling Behavior Questionnaire (CBQ) and histogram of cycling crashes. Results are grouped according to the city population size.

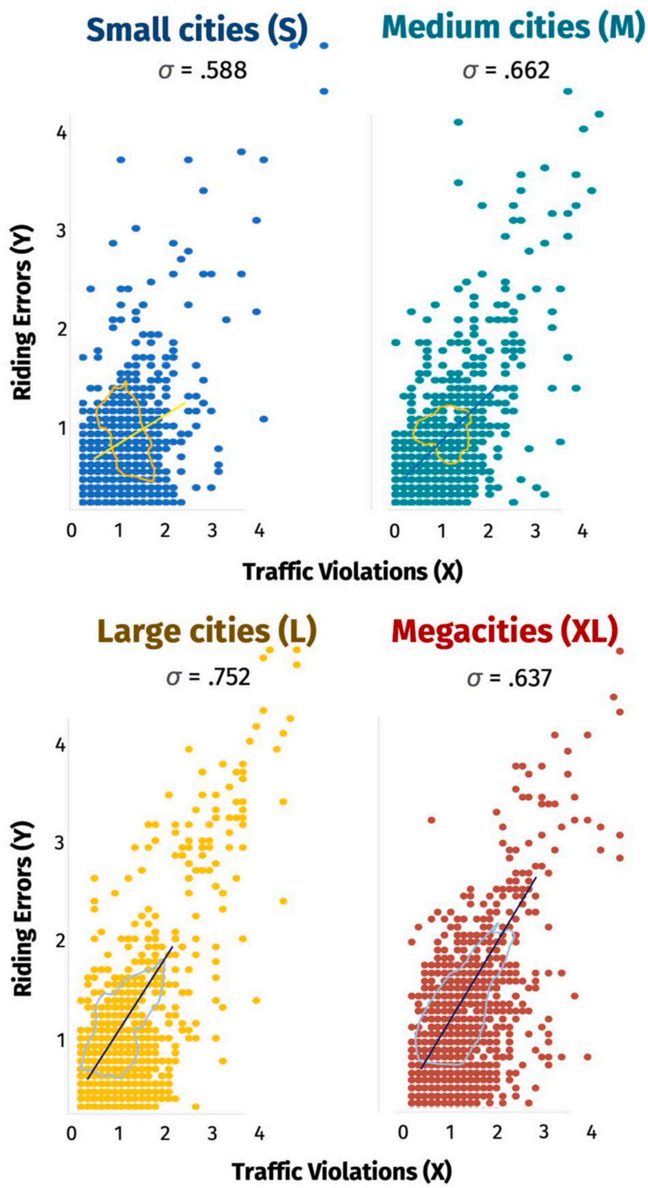

Fig. 3. Bivariate (XY) correlations of risky cycling behaviors (deliberate and non-deliberate), measured with the Cycling Behavior Questionnaire (CBQ) in different sized cities. Each spot represents a cluster of ±5 cases.

4.1. Do riders 'match' their behaviors to the context?

The outcomes of this extensive data collection show that, in particular, cyclists from bigger urban areas (especially in the case of megacities) consistently self-report more frequent risky road behaviors, including both traffic violations and errors, than cyclists from any other city size-based groups (see Tables 3 and 4). There were no such significant differences in self-reported positive behaviors between study groups, although a slight trend ($p \approx 0.050$) was observed when comparing cyclists from small cities and those from megacities. Although this particular finding will be discussed further, it is worth anticipating that one of the common literature-endorsed assumptions supporting this goes beyond greater exposure rates.

Particularly, previous studies such as Gao et al. (2018), Graells-Garrido et al. (2021), Kraus and Koch (2021), and Useche et al. (2018c), underscore several key 'critical' issues of large cities, such as the complexity of bike lane networks, stress-related factors, high environmental stimulation degrees, and the latency of road conflicts, as potential hindrances to both safe cycling patterns and outcomes. Regarding safety indicators (i.e., self-reported cycling crashes), cyclists from small cities self-reported significantly fewer cycling crashes than cyclists from cities with a population of 200,000 or more. In addition, it is worth highlighting the non-significant nature of the differences between cyclists from medium and large cities in all the behavioral and crash-related variables used in this study. Hereunder, this discussion is developed by first attending to the correlation between the study variables, both in the general sample and divided by city size, and afterward, analyzing the main differences found between the groups.

4.2. City size, riding behavior, and crash involvement

Firstly, the descriptive bivariate correlation analysis strengthens the findings of previous literature regarding cycling behavior and crash involvement. In this regard, the association between the three dimensions of the CBQ (positive correlation between risky behaviors and negative correlation with positive behaviors) has been reported in previous applied studies (Useche et al., 2021b; Useche et al., 2022a), higher rates of risky behaviors correlate with higher self-reported involvement in cycling crashes, and higher rates of protective behaviors are associated with lower self-reported crash involvement (O'Hern et al., 2021; Useche et al., 2018a; Useche et al., 2019b; Wang et al., 2020; Zheng et al., 2019).

The core independent variable referred to in this study (i.e., city size) significantly correlated ($p < .001$) with all the study variables. More specifically, it was found that cyclists from bigger cities present more cycling hours but lower trip lengths ($p < .001$). Similarly, they self-reported significantly ($p < .001$) higher rates of violations, errors, and cycling crashes and lower rates of positive behaviors. After this bivariate analysis, the effect of the city size on the study-dependent variables is

Table 5
Variables included in the model, estimates, significance levels, and 95% confidence intervals for bootstrap bias-corrected values of the path model.

Study variable			SPC[a]	S.E.[b]	C.R.[c]	p[d]	Bootstrap bias-corrected values[e]				
							Est[f]	S.E.[b]	95% CI[g]		p[d]
Direct effects											
City Size	→	Traffic Violations	0.111	0.005	8.634	***	0.112	0.004	0.087	0.137	**
City Size	→	Riding Errors	0.107	0.004	7.710	***	0.108	0.004	0.073	0.125	**
City Size	→	Cycling Crashes	−0.003	0.010	−0.263	0.793	−0.003	0.001	−0.024	0.024	0.916
Mediated effects											
Traffic Violations	→	Cycling Crashes	0.137	0.037	8.033	***	0.138	0.039	0.103	0.173	**
Riding Errors	→	Cycling Crashes	0.183	0.039	10.852	***	0.184	0.040	0.147	0.210	**

Notes: [a] SPC = Standardized Path Coefficients (can be interpreted as b-linear regression weights); [b] S.E. = Standard Error; [c] CR = Critical Ratio; [d] *p*-value: *significant at the level $p < .050$; **significant at the level $p < .010$; ***significant at the level $p < .001$; [e] Bootstrapped (bias-corrected) model; [f] Bootstrapped (bias-corrected) model standardized estimates; [g] Confidence Interval at the level 95% (lower bound – left; upper bound – right).

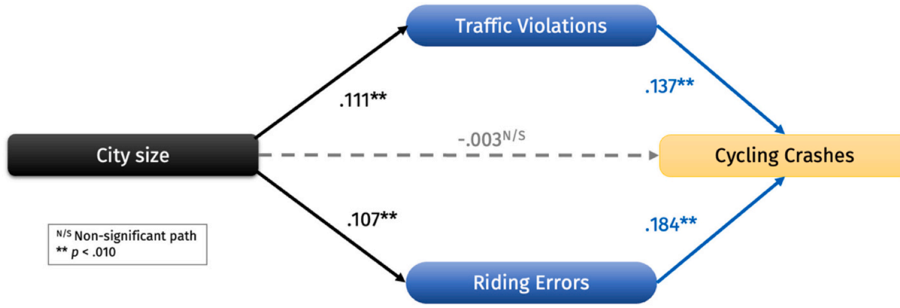

Fig. 4. Path model- Bootstrap (bias-corrected) parameter estimates. Squares represent non-latent factors, and ellipses represent latent variables. Note: All listed estimates in solid lines are significant (as shown in Table 5).

discussed. From a theoretical point of view, the great homogeneity found in terms of city size-based trends (see Figs. 3 and 4) drives us to consider that, in broad terms, the right approach may not be that a group of cyclists is more or less 'risky' than the others, but that the environment in which one cycles pushes riders into performing behaviors considered risky. This is also supported by previous research, which ensures that cyclists act differently depending on the environment they cycle (Molina-Soberanes et al., 2019; Reynolds et al., 2009). However, it should be borne in mind that this is the first study assessing self-reported behavior and cycling crashes according to the size of the city in which they ride. Therefore, this is just an assumption, and further studies should confirm whether the same cyclist would change their behavior after being used to riding in a city of a different size.

4.3. Could bigger cities get 'riskier' riders than the others?

As mentioned in the introduction, interventions in support of active mobility have predominantly taken place in highly populated urban environments, where cycling infrastructure tends to be comparatively over-developed in comparison with most smaller cities (Brüchert et al., 2022; Mertens et al., 2017; Sharma et al., 2019). However, the infrastructure-based approach tends to remain reductionist in the absence of a multifactorial point of view. In addition, the raw effect of city size on behavior and the number of crashes remains under-explored in the literature (Sharma et al., 2019; Winters et al., 2010; Zhang et al., 2022).

Bearing in mind the aforementioned, and regardless of having a relatively extensive sample size, a categorical response to this question might exceed the scope of the data provided by this study. However, the gathered data allows us to provide some insights in this regard. In the present study, which explores a single (but relevant) part of this question, cyclists from small cities (population of 50,000 or lower) have been shown to self-report the lowest rates of violations and errors compared with cyclists from the rest of the groups (i.e., 50,000 or more inhabitants) and fewer cycling crashes compared with cyclists from large cities and megacities (i.e., > 200,000 people; see Tables 3 and 4). This is despite research suggesting small cities are more likely to favor cars over bikes (Brüchert et al., 2022).

Secondly, the 'safety in numbers' phenomenon should be considered (see further below; Jacobsen, 2003; Jacobsen et al., 2015; Macmillan and Woodcock, 2017; Winters et al., 2018), by which smaller cities would be a riskier environment to ride in. Some studies summarize this as 'the more people cycling in a city, the safer cycling in that city' (Jacobsen, 2003; Jacobsen et al., 2015). Consequently, many people may choose not to cycle due to a perception of unsafe cycling conditions (Branion-Calles et al., 2020; Macmillan and Woodcock, 2017). Additionally, individuals cycling in these hazardous environments might become more skillful (Castro et al., 2020), potentially preventing or regulating their influence on risky cycling behaviors and crash risk.

Back to the present study data, our participant cyclists from megacities self-reported more violations and errors compared with the other groups (see Tables 3 and 4). One potential explanation for this comparatively riskier behavior taking place in bigger cities could be linked to the fact that better infrastructure tends to provide a safer riding environment, giving sense to both the afore-described 'safety in numbers' phenomenon (Macmillan and Woodcock, 2017; Winters et al., 2018), and risk management-related approaches such as the risk homeostasis theory. According to the last, cyclists may tend to adapt their behavior toward greater or lesser risk-taking based on how they subjectively perceive the risk (Constant et al., 2012; Lardelli-Claret et al., 2003).

Back to the study data, and although not applicable to all cases, cyclists riding in larger cities are more likely to count on friendlier infrastructures which, in turn, might contribute to increased safe environmental perceptions generating a feeling of overconfidence and, therefore, enhance riskier behavioral patterns (Kelly et al., 2020; Winters et al., 2018). However, this seems not to apply to the case of positive behaviors (e.g., avoidance of riding under adverse weather conditions, helmet wearing) which, are perhaps more internally driven (Thompson et al., 2000). On the other hand, actual risky-riding behaviors, (e.g., running red lights, riding on the pavement) are driven more by external factors, like the physical and traffic environment (McIlroy et al., 2022; Useche et al., 2018c).

Additionally, and although they were not directly considered in this study, common distracting features (e.g., billboards, over-signalized paths) are more present in large cities and play a mediating role in risky behaviors (Dukic et al., 2013; Heeremans et al., 2022; Useche et al., 2018a; Wolfe et al., 2016), which in turn influences the vehicle crash rates of cyclists (O'Hern et al., 2021; Useche et al., 2018a; Useche et al., 2019b; Wang et al., 2020; Zheng et al., 2019). There is also research demonstrating higher crash risks for active transportation users in urban areas with higher compared to lower building densities (Branion-Calles et al., 2020). Coherently with previous empirical literature, and unlike self-reported risky riding behaviors and crash outcomes, significant differences in positive behaviors are not commonly found (Alonso et al., 2021). However, there was still a pseudo-significant statistical difference ($p \approx 0.050$) between small cities and megacities (see Table 4), suggesting that the matter could not be despised in view of its potential theoretical plausibleness.

4.4. A 'behaviorally-mediated' effect

One of the key features of the present research was to assess the statistical effects of city sizes and risky cycling behaviors on (self-reported) crash-related outcomes of urban cyclists. In brief, the findings suggest that, far from having found a direct statistical path/effect ($p >$ .900), the relationship between city sizes and crash outcomes is mediated by bicycle riders' propensity to perform risky riding behaviors.

This is, indeed, consistent with previous behavior questionnaire (BQ) studies using predictive techniques (e.g., Path, SEM, MGSEM, MLR methods) to assess the role of behavioral issues on cycling crashes, in which risky riding contributors remain the most relevant issue alongside demographic factors, such as age and gender (Hezaveh et al., 2018; Li et al., 2021; Lijarcio et al., 2022). For instance, after also controlling for demographics and exposure, multiple linear regression (MLR) based studies explaining cycling crashes have shown great predictive value for risky road behaviors (but especially for errors; McIlroy et al., 2022; O'Hern et al., 2021), and confirmatory modeling (i.e., path, SEM and MGSEM) procedures have systematically endorsed the predictive value of behavioral contributors to self-reported crashes across the five continents (Useche et al., 2022a; Useche et al., 2018c; Zheng et al., 2019).

On the other hand, the role of city size on behavioral outcomes remains largely underexplored, despite providing broad and relatively consistent patterns suggesting the need for action to face the challenging 'safety in density effect' and other typical hindrances targeted in larger urban areas across the few studies so far conducted with cyclists (Thompson et al., 2019; Winters et al., 2018). Nevertheless, the statistically endorsed hypotheses of this study regarding cycling behavior as a potential mediator between infrastructural factors – city size being just one of them – and mid-term safety outcomes of cyclists (which are coherent with the limited empirical research that does exist) make us think about the need to further explore the matter 'beyond numbers'.

Finally, in order to accurately interpret the study data, it should be considered that the city classification adopted for the present study is based on population size, but the built environment, gender, psychosocial and cultural issues have been also consistently claimed to be relevant contributors of cycling behavioral outcomes (Bimbao and Ou, 2022; Bishop et al., 2023; Useche et al., 2022a, 2022b). Therefore, there are some potential explications to the results (e.g., *safety in numbers*) that may vary according to the specific traits of each region, as well as further improvements other than built environment for cycling, including actions at the social level, promotion of cycling culture, and enforcement (Constant et al., 2012; Mölenberg et al., 2019; Pucher and Buehler, 2016; Yang et al., 2010).

Also in this regard, there are differences in the response rate of each city size (small, medium, large, megacity) depending on the specific characteristics of each country, preventing us from potentially overgeneralizing the current statistical outcomes. With this in mind, caution must be applied until more scientific evidence arrives. Future studies should evaluate whether cultural and built-environment differences between cities may influence the parameters analyzed in the present study.

5. Conclusions

The outcomes of this study analyzing the data provided by 5705 cyclists from >300 urban areas in 18 countries suggest that city size accounts for cycling safety outcomes through statistical associations (Pearson's partial correlations), differences (ANOVA testing), and confirmatory predictive relationships (path analysis) through statistical mediation via cycling behavioral patterns.

Specifically, we found that cyclists from small cities (population of 50,000 or less) self-report significantly lower rates of risky behaviors and fewer cycling crashes compared with cyclists from larger urban areas.

On the other hand, and beyond cyclists' age and exposure, 'riskier' profiles were consistently found in larger cities in terms of both self-reported cycling crashes and risky riding behaviors (i.e., traffic violations and errors). No such differences were found not in terms of self-reported protective behaviors. The results of the present study highlight the need to target cycling safety-threatening dynamics, especially in larger cities.

CRediT authorship contribution statement

Sergio A. Useche: Visualization, Conceptualization, Supervision, Data curation, Investigation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing. **Francisco Alonso:** Investigation, Resources, Funding acquisition, Software, Validation, Writing – review & editing. **Aleksey Boyko:** Investigation. **Polina Buyvol:** Investigation. **Isaac D. Castañeda:** Investigation. **Boris Cendales:** Investigation, Visualization, Writing – original draft. **Arturo Cervantes:** Investigation, Visualization. **Tomas Echiburu:** Investigation. **Mireia Faus:** Investigation, Methodology, Software, Validation. **Javier Gene-Morales:** Investigation, Data curation, Formal analysis, Validation, Writing – original draft. **Jozef Gnap:** Investigation, Supervision. **Mohd K.A. Ibrahim:** Investigation. **Kira H. Janstrup:** Investigation, Conceptualization, Supervision. **Irina Makarova:** Investigation. **Miroslava Mikusova:** Investigation. **Mette Møller:** Investigation, Validation, Writing – original draft. **Steve O'Hern:** Investigation, Conceptualization, Data curation, Supervision, Writing – review & editing. **Mauricio Orozco-Fontalvo:** Investigation, Validation. **Ksenia Shubenkova:** Investigation. **Felix W. Siebert:** Investigation, Conceptualization, Supervision, Writing – original draft. **Jose J. Soto:** Investigation, Visualization. **Amanda N. Stephens:** Investigation, Conceptualization, Validation. **Yonggang Wang:** Investigation. **Elias S. Willberg:** Investigation, Validation. **Philipp Wintersberger:** Investigation, Data curation. **Linus Zeuwts:** Investigation. **Zarir H. Zulkipli:** Investigation. **Rich C. McIlroy:** Supervision, Investigation, Conceptualization, Data curation, Methodology, Writing – original draft.

Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

Acknowledgments

The authors of this study would like to thank Rowena O'Donnell (certified translator) for the professional proofreading of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtrangeo.2023.103754.

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