Associations between individual characteristics, availability of bicycle infrastructure, and city-wide safety perceptions of bicycling: a cross-sectional survey of bicyclists in 6 Canadian and U.S. cities

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Abstract

Safety concerns are a primary deterrent to bicycling. Bicycle infrastructure is both preferred and safer for bicycling. In this paper, we examine the association between availability of bicycle infrastructure and perceptions of bicycling safety amongst over 3,000 bicyclists living in six large Canadian and US cities. In three repeat cross-sectional surveys (2012, 2013 and 2014), adults living in Boston, Chicago, New York, Montreal, Toronto, and Vancouver were surveyed about their bicycling habits, safety perceptions, and demographic characteristics as part of the International Bikeshare Impacts on Cycling and Collisions Study (n = 16,864). Participants were assigned a measure for the availability of bicycle infrastructure (a component of Bike Score® called Bike Lane Score, range 0-100) based on their residential postal code. We used weighted multinomial regression models to examine associations between perceived bicycling safety and spatial access to bicycle infrastructure accounting for sociodemographic characteristics amongst those who report bicycling in the past month (n = 3,446; weighted n = 3,493). Overall, 57.9% perceived bicycling in their city as safe, 15.1% as neutral, and 27.0% as dangerous. Our model indicates that, within cities, bicyclists with greater bicycle infrastructure availability had improved odds of perceiving bicycling as safe. Specifically, a 10-unit increase in Bike Lane Score was associated with 6% higher odds of a bicyclist perceiving the safety of bicycling as safe compared to neutral. Bicyclists who are male, younger, lower income, have young children, have a high-school education, and bicycle more frequently are predicted to be more likely to perceive bicycling in their city to be safe. These results suggest that increasing the availability of bicycle facilities by expanding bicycling networks may result in increases in perceptions of bicycling safety for existing bicyclists, but also that individual characteristics play a substantial role in bicycling safety perceptions.

Keywords

Bicycling; Bicycle infrastructure; Perceived safety; Bike Score; Built environment

Highlights

- Modelled bicyclists' safety perceptions using large population survey in Canada and US
- Access to bicycle infrastructure is associated with higher perceived bicycling safety
- Male and/or younger bicyclists are associated with higher perceived bicycling safety
- Expanding bicycling infrastructure may result in increased bicyclists' perceptions of safety

1.0 Introduction

Research indicates that there are significant societal benefits for bicycling, primarily due to health benefits of increased physical activity (de Hartog et al., 2010; Götschi et al., 2016; Mueller et al., 2015). Within cities in Canada and the United States (US), bicycling uptake is generally low, with only 1.3% and 0.6% of workers reporting that they commute by bicycle to work, in Canada and the US respectively (McKenzie, 2014; Statistics Canada, 2013a). Ridership levels in European cities are much higher than in Canada and the US (Bassett et al., 2008; Pucher and Buehler, 2008; Pucher and Dijkstra, 2003), suggesting there is substantial potential for increased bicycling.

Safety concerns are a primary deterrent to bicycling (Heinen et al., 2010; Willis et al., 2014). Previous research has shown that the perceived safety of bicycling varies by age, gender and bicycling experience, across a range of different bicycling environments (Bill et al., 2015; Chataway et al., 2014; Hels and Orozova-Bekkevold, 2007; Lawson et al., 2013; Manton et al., 2016; Møller and Hels, 2008; Parkin et al., 2007). Bicycling environments that provide bicycle infrastructure tend to be perceived as safer than those that require bicycling in mixed traffic (Chataway et al., 2014; Manton et al., 2016; Parkin et al., 2007; Winters et al., 2011). Increasing access to bicycle infrastructure has been promoted as a potentially effective means of increasing bicycling mode share in cities with low bicycling uptake (Buehler and Pucher, 2012; Dill and Carr, 2003; Pucher and Buehler, 2008, 2006). Implementing bicycle infrastructure has the potential to increase trips from new bicyclists, as well as existing (National Institute for Transportation and Communities, 2014; Noland, 1995).

Studies of the association between bicycling environments and perceived safety tend to focus on comparing different infrastructure or routes within the road network. These studies are important for understanding how specific infrastructure designs may improve perceived personal safety at a specific time and place, but do not provide insight into their associations with general perceptions of bicycling safety. More generalized perceptions of bicycling safety across a larger geographic context (e.g., across a neighbourhood or city) may be associated with individuals bicycling, or how often they bicycle (Lawson et al., 2013). In this study we aim to examine the associations between individual characteristics, bicycling infrastructure availability, and city-wide perceptions of bicycling safety across 6 major cities in the US and Canada. We use survey data from the International Bikeshare Impacts on Cycling and Collisions Study (IBICCS) (Fuller et al., 2014) to measure perceived safety and individual characteristics, and Bike Lane Score, a component of the Bike Score Index (Winters et al., 2016), to measure bicycle infrastructure availability.

2.0 Materials and Methods

2.1 IBICCS

IBICCS was designed to evaluate the health impacts of public bicycle share programs. The study protocol is published elsewhere (Fuller et al., 2014). Briefly, it included three repeat, cross-sectional online panel surveys (in Fall of 2012, 2013, and 2014) of residents across eight cities: Montreal, Toronto, Boston, New York, Vancouver, Chicago, Detroit and Philadelphia (n=23,901). Each survey collected information on sociodemographic characteristics, health and travel behaviour, safety perceptions, and residential and work locations (post codes). The study aimed to survey participants within a defined sampling area, which were generally smaller subsets of the city proper based on where public bike share stations were (or potentially would be) implemented (see Fuller et al., 2014 for details). In this analysis we include all participants living within the city boundaries. The IBICCS data collection was approved by the Research Ethics Committee of the Centre Hospitalier de l'Université de Montréal.

2.2 Study Area

Our study area includes the six IBICCS cities for which we have comparable data on bicycle infrastructure: Boston, Chicago, New York, Montreal, Toronto and Vancouver (Figure 1). In 2012 each city had a low bicycling rate, with between 0.8 to 4.4% of workers reporting that they commute by bicycle (Table 1).

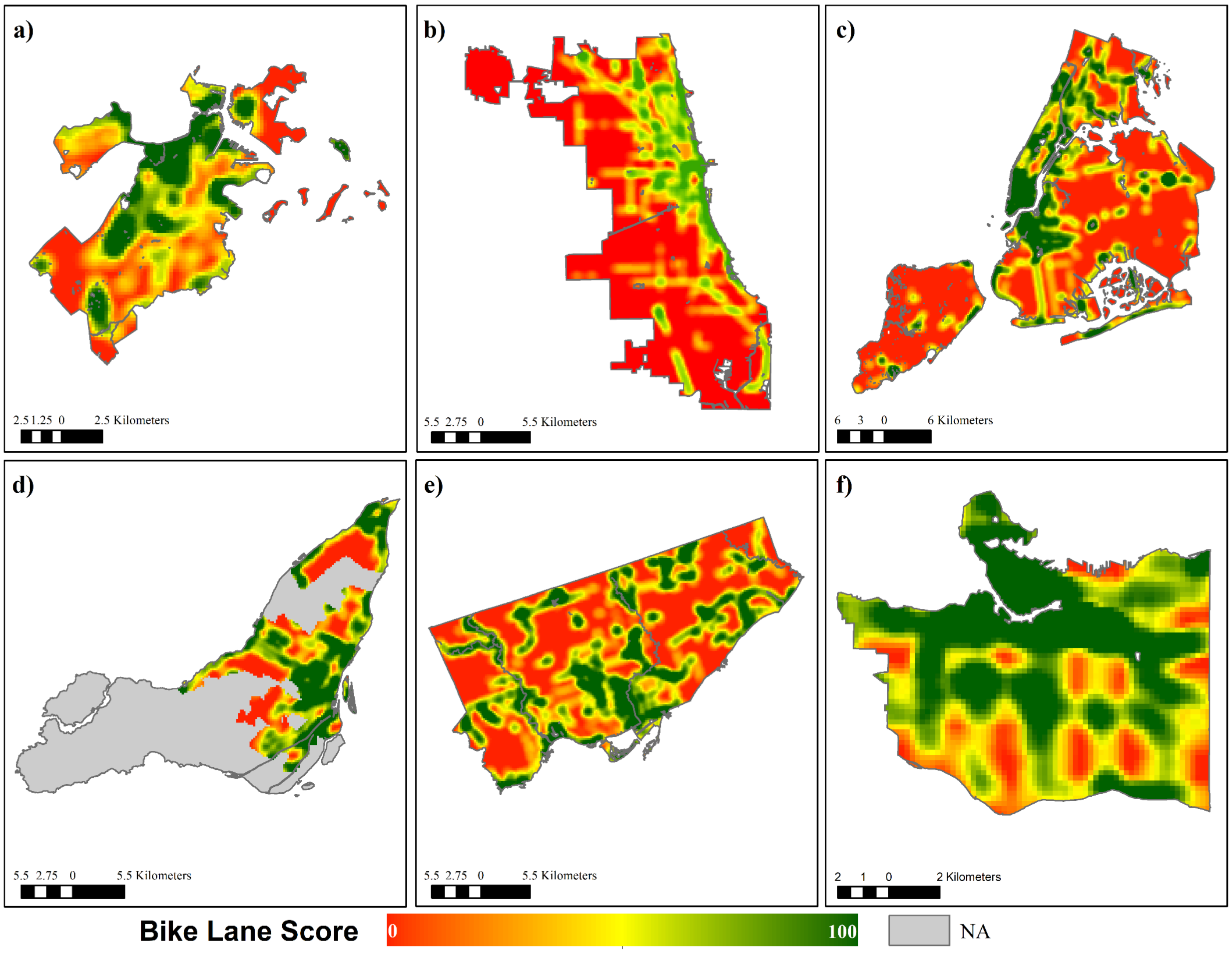

Figure 1: IBICCS study area boundaries and the spatial distribution of bicycle infrastructure, using Bike Lane Score as a proxy. The study areas include the cities of: a) Boston, b) Chicago, c) New York, d) Montreal, e) Toronto, f) Vancouver. Bike Lane Score can range from 0-100, where 100 indicates close proximity, or greater availability of bicycle infrastructure and 0 indicates no bicycle infrastructure within 1-km. NA indicates an area where Bike Lane Score data were not available. Note that cities are of different geographic extents as indicated by scale bars.

City	Boston	Chicago	New York	Montreal	Toronto	Vancouver
Area (km^2)	125.1	589.3	783.5	366.4	630.6	114.9
Total population[a]	619,662	2,702,471	8,199,221	1,649,519	2,615,060	603,502
Working population[b]	317,930	1,213,901	3,685,786	727,455	1,174,610	294,790
Proportion who commute by bicycle[b]	1.7%	1.3%	0.8%	3.2%	2.2%	4.4%

Average fatalities per million bicycle to work trips (2007-2012)[c]	1.16	1.38	2.94	0.60	NA	1.10
City-wide Bike Lane Score (2012)						
Mean	46	20	29	56	39	68
Median	40	6	11	61	30	74
Q1	14	0	0	19	1	44
Q3	78	33	54	100	72	100
IQR	64	33	54	81	71	56
Range	0-100	0-100	0-100	0-100	0-100	0-100

[a] Boston, Chicago and New York, based on 2008-2012 American Community Survey 5-year estimates (US Census Bureau, 2017a), Montreal, Toronto, Vancouver, based on Census 2011 (Statistics Canada, 2012a, 2012b, 2012c);[b] Boston, Chicago and New York, based on 2008-2012 American Community Survey 5-year estimates (US Census Bureau, 2017b), Montreal, Toronto, Vancouver statistics are based on 2011 National Household Survey (Statistics Canada, 2013b, 2013c, 2013d); [c] Based on previous study which, for Canadian cities compiled fatality and exposure data directly from the cities, and for American cities obtained data from National Highway Traffic Safety Administration Fatality Data (Urban Systems, 2015);NA: Not Available

Table 1: Descriptive information regarding city populations, bicycling mode shares, and distributions of Bike Lane Score for 6 cities IBICCS participants were recruited.

2.3 Measures

Safety Perceptions

Only those participants who reported bicycling in the previous month were asked their perceptions of bicycling safety. Bicycling safety perceptions were measured based on a question which asked bicyclists “Overall, how safe do you think bicycling is in your city?” Respondents could answer based on a 5-point scale: 1-“Very Safe”, 2- “Somewhat safe”, 3-“Neutral”, 4- “Somewhat dangerous” and 5-“Very Dangerous.” We collapsed these responses into a 3-point scale consisting of “Safe” (1+2), “Neutral” (3) and “Dangerous” (4+5).

Bicycling Infrastructure

We use a component of the Bike Score index, called Bike Lane Score, to measure the availability of bicycling infrastructure at a given location within the study area (Figure 1). Bike Lane Score (2012, 100 m grids) was provided by RedFin Real Estate and represents the only internationally available standardized infrastructure dataset at the time the IBICCS survey data were collected. Bike Lane Score is a normalized index of a location’s proximity to bicycle infrastructure. Bicycle infrastructure data used in this index were provided by municipal governments, and includes the following: on-street painted bicycle lanes, off-street trails, separated bicycle paths, and neighbourhood bikeways (Winters et al., 2016). To compute Bike Lane Score for a given location, the length of all infrastructure nearby were summed and weighted based on a distance decay function where infrastructure outside 1 kilometre were weighted 0. Infrastructure types that are separated from traffic are weighted double compared to those that are not. The raw weighted lengths were then normalized to a score between 0-100, with higher Bike Lane Scores indicating greater availability of bicycle infrastructure and a Bike Lane Score of 0 indicating no infrastructure within 1 kilometre. Past work shows that Bike Lane Score is positively correlated to journey-to-work bicycle mode share in 24 Canadian and US cities (Winters et al., 2016).

The distribution of Bike Lane Scores within each city indicated that many areas still lacked bicycle infrastructure. The median Bike Lane Score within each city ranged from a low of 6 to a high of 74 (Table 1). Chicago, New York and Toronto had lower median Bike Lane Scores as compared to Boston, Montreal or Vancouver, but the spatial extent of Bike Lane Score in these cities was much greater (Figure 1). Each city tended to have higher Bike Lane Scores in the core area as compared to the surrounding area. Survey participants were assigned a Bike Lane Score based on the location of their residence as derived from postal codes.

Covariates

Potential confounders were identified a priori based on sociodemographic characteristics that could influence both choosing to live in bicycling supportive areas, as well as to differences in the perceived safety of bicycling. Selected variables were based on a consideration of individual level confounding variables previously used in research on the effect of proximity to bicycle infrastructure and bicycle use (Krizek and Johnson, 2006) and include age (continuous), gender (male or female), having young children (yes or no), income (under $50 K, $50-100 K, over $100 K, refuse), education (high school or less, or any college/university), and ethnicity (White/Caucasian or Asian / Insular of the Pacific or Black/African/African-American or Hispanic/Latino/Spanish or Other).

We calculated average daily bicycling frequency as a measure of individual bicycling exposure. Specifically, participants were asked to recall the average number of days per week in the last month they used a given mode for at least 10 minutes at time to go from place to place, and then how much time they usually spent on one of those days using that mode. An average daily bicycling frequency measure was calculated for each participant, and outliers (n = 56) were truncated to a maximum of 3 hours per day.

2.4 Sample

Overall 16,864 of 23,901 IBICCS survey participants lived within the boundaries of the six cities, and these participants were assigned post-stratification weights based on comparing the age and sex distribution of each city as defined by census data, to the age and sex distribution of our sample within each city. We removed participants that did not have a valid Bike Lane Score (n=374; weighted n = 356) and those that reported spending a combined total of greater than 16 hours per day using any form of transportation (n=53; weighted n=55). Of the remaining participants, those who report bicycling in the past month had responses for bicycling safety perceptions and were eligible to be studied (n=3,561; weighted n = 3,608). Finally, participants that had missing data on sociodemographic characteristics apart from income were removed (n=113; weighted n = 111). We maintained those who refused to provide income (n=243; weighted n = 238). Our final sample of bicyclists included 3,446 participants, representing a weighted population of 3,493.

2.5 Statistical Analysis

Weighted descriptive statistics were generated for all variables, overall and stratified by city. Weighted multinomial logistic regression was used to analyze the association between bicyclists' spatial access to bicycling infrastructure (as represented by Bike Lane Score) and perceptions of bicycling safety (ie., safe, neutral, dangerous), controlling for sociodemographic characteristics.

We included a fixed effect for city which is appropriate when adjusting for clustering with small numbers, allowing us to pool our sample rather than run city-specific models (Cerin, 2011). Modeling was done using Proc SURVEYLOGISTIC (SAS 9.4) with link=GLOGIT to specify a multinomial outcome. We applied post-stratification weights. We fit individual models for each covariate, followed by an adjusted model containing all variables, with 'Neutral' set as the reference category. Each exponentiated coefficient represents the within-city effect of a variable on the odds of rating bicycling as neutral compared to safe, or dangerous compared to safe. We tested all two-way interaction effects between Bike Lane Score and sociodemographic variables and found no significant interactions.

We plotted the marginal effects of each covariate to visualize the predicted relationship between each covariate and perceived bicycling safety. Here we define marginal effects as the adjusted model's prediction of perceived safety over the range of values for a specific covariate, when other covariates are held to a representative value (mean or mode). These plots can be conceptualized as the predicted effect of a given variable on the perceived safety of bicycling for an *average* bicyclist.

Since infrastructure availability is a readily modifiable factor, we create a scenario to quantify the predicted effect of increasing the bicycling infrastructure availability on perceptions of bicycling safety. In this scenario we first defined a hypothetical sample of bicyclists where each individual was characterized by a unique combination of the levels of the independent variables in the adjusted model (including gender, age, bicycling frequency, income, education, having children, ethnicity, and city of residence). We then used the adjusted model to predict the probability that each bicyclist in this sample perceived bicycling in their city to be safe, neutral and dangerous if they resided in an area with no bicycling infrastructure available within 1 kilometre (Bike Lane Score of 0) and also if they resided in an area with high quality bicycling infrastructure available nearby (Bike Lane Score of 100). We then subtract the predicted probabilities of safe, neutral and dangerous when Bike Lane Score is 0, from when Bike Lane Score is 100, for each individual. This difference represents the predicted effect that increasing Bike Lane Score from 0 to 100 would have on perceived bicycling safety, where a positive value represents an increase in probability of a given perceived safety rating, and a negative value a decrease. The absolute difference in probabilities when Bike Lane Score is 100 versus 0, is repeated across all individuals in our hypothetical sample and plotted in a boxplot to visualize the predicted effect of increasing the availability of bicycling infrastructure of an area. All plots were created in R 3.4.1(R Core Team, 2017).

3.0 Results

3.1 Sample Characteristics

Across the six cities, most bicyclists were male (61.1%), employed full-time (57.7%), had at least some post-secondary education (90.9%), and did not have any children aged 17 years or under (74.4%) (Table 2). A majority of bicyclists had a driver's license (87.8%), as well as had access to a motor vehicle (69.4%). Most had cycled 1-2 days per week in the previous month (56.6%) (Table 2). Compared to the full IBICCS sample (bicyclists and non-bicyclists) bicyclists were disproportionately male (61.1% compared to 47.7% of full sample) and under the age of 55

(81.0% compared to 69.6% of full sample) but otherwise were similar in sociodemographic characteristics. Overall, 22.1% report bicycling in the past month; 20.8% in Boston, 22.9% in Chicago, 23.4% in Montreal, 20.3% in New York, 22.6% in Toronto, and 22.2% in Vancouver.

		Boston	Chicago	New York	Montreal	Toronto	Vancouver	Overall
	Weighted Total (n)	222	785	715	467	887	417	3493
					% of n			
Safety Perception	Safe	45.3	61.7	55.7	56.7	52.7	73.2	57.9
	Neutral	14.2	12.5	14.4	15.2	17.4	16.5	15.1
	Dangerous	40.5	25.8	29.8	28.0	29.8	10.4	27.0
Residential Bike Lane Score	25 or under	4.4	33.2	12.4	16.1	30.6	11.1	21.5
	26 - 50	20.4	28.5	16.8	12.2	22.0	11.0	19.7
	51 - 75	11.0	22.5	20.7	18.1	16.8	19.0	19.0
	75-100	64.3	15.8	50.0	53.6	30.6	58.8	39.8
Gender	Female	45.2	37.1	40.5	39.8	38.2	36.4	38.9
	Male	54.8	62.9	59.5	60.2	61.8	63.6	61.1
Age	18-24	13.1	25.0	23.3	14.8	22.8	24.4	21.9
	25-34	14.4	19.2	24.3	30.3	22.3	23.9	22.8
	35-44	15.8	17.9	20.0	16.9	19.3	16.9	18.3
	45-54	18.1	17.2	17.3	21.9	17.6	17.1	18.0
	55 or older	38.5	20.7	15.0	16.2	18.0	17.8	19.0
Income	Under $50 K	21.4	33.8	29.7	40.4	30.9	31.1	32.0
	$50-100 K	33.5	35.8	34.0	37.5	33.3	37.2	35.0
	Over $100 K	38.0	25.6	30.4	14.6	27.4	24.1	26.2
	Refuse	7.1	4.8	5.9	7.5	8.4	7.6	6.8
Ethnicity	White/Caucasian	78.3	68.5	64.6	83.5	71.2	58.0	69.8
	Black/African/African-American	7.3	12.2	9.9	1.9	2.6	0.8	6.3
	Hispanic/Latino/Spanish	4.3	9.4	11.3	2.1	2.0	5.1	6.1
	Asian / insular of the Pacific	9.3	8.8	12.1	7.4	17.6	30.9	14.2
	Other	0.9	1.1	2.1	5.0	6.7	5.1	3.7
Children Under 18	Children	17.0	23.7	29.6	23.1	26.4	28.2	25.6
	No Children	83.0	76.3	70.4	76.9	73.6	71.8	74.4
Education	Any College or University	97.2	92.0	92.2	88.9	91.2	85.2	90.9
	High School or Less	2.8	8.0	7.8	11.1	8.8	14.8	9.1
Employment	Full-Time	65.9	59.0	57.5	51.0	59.2	56.1	57.7
	Part-Time	7.6	9.5	9.4	7.1	9.9	11.8	9.4
	Self-employed	5.4	6.9	12.3	11.5	9.9	7.1	9.3
	Student	8.6	10.3	11.9	13.1	8.9	10.2	10.5
	Unemployed/Retired/Other	12.6	14.1	8.6	17.3	11.8	14.6	12.8
	Refuse	0.0	0.2	0.2	0.0	0.4	0.2	0.2
Driver's License	Yes	96.6	89.7	84.6	83.3	87.8	90.0	87.8
	No	3.4	9.8	15.2	16.6	11.9	9.6	11.9
	Refuse	0.0	0.5	0.3	0.1	0.3	0.3	0.3

Access to Motor Vehicle	Yes	77.1	76.7	54.4	63.3	70.1	82.9	69.4
	No	22.8	22.3	45.2	36.3	29.0	16.7	29.9
	Refuse	0.1	1.0	0.4	0.4	0.8	0.4	0.6
Average Days per Week Cycled in Previous Month	1 to 2	59.2	60.8	57.0	48.0	55.7	58.2	56.6
	3 to 5	30.0	31.5	36.3	44.4	33.6	33.7	34.9
	6 to 7	10.8	7.7	6.7	7.7	10.7	8.1	8.5
Average Daily Bicycling Minutes in Previous Month	15 minutes or less	49.7	48.4	43.4	48.0	47.8	45.5	46.9
	15-30 minutes	31.2	23.4	24.8	26.5	21.3	25.1	24.3
	30-60 minutes	14.4	17.0	18.1	16.6	21.4	19.4	18.4
	>60 minutes	4.8	11.3	13.7	8.9	9.4	10.0	10.4
	Mean (minutes)	23.5	28.2	31.7	27.3	29.0	28.0	28.7
	Minimum (minutes)	0.1	0.1	0.1	0.3	0.3	0.1	0.1
	Maximum (minutes)	180.0	180.0	180.0	180.0	180.0	180.0	0.0

Table 2: Weighted values for sociodemographic characteristics of the subsample of respondents from the IBICCS sample who reported bicycling in the previous month.

A Bike Lane Score lower than 50 indicates minimal bike infrastructure was available near a bicyclists' residence (Walk Score, 2018). A considerable proportion of bicyclists (41.2%) had a Bike Lane Score lower than 50, with variability by city. Toronto and Chicago had the highest proportion of bicyclists with limited access (52.6 % and 61.7% with a Bike Lane Score lower than 50, respectively), while the remaining cities had similar proportions ranging between 22.1% and 29.2%.

Overall, most bicyclists perceived bicycling in their city to be safe. Specifically, 57.9% of bicyclists reported bicycling in their city as safe, 15.1% as neutral, and 27.0% as dangerous (Figure 2). A larger proportion of bicyclists in Boston perceived bicycling to be dangerous (40.5%) and Vancouver was perceived as safer (73.2%) (Figure 2).

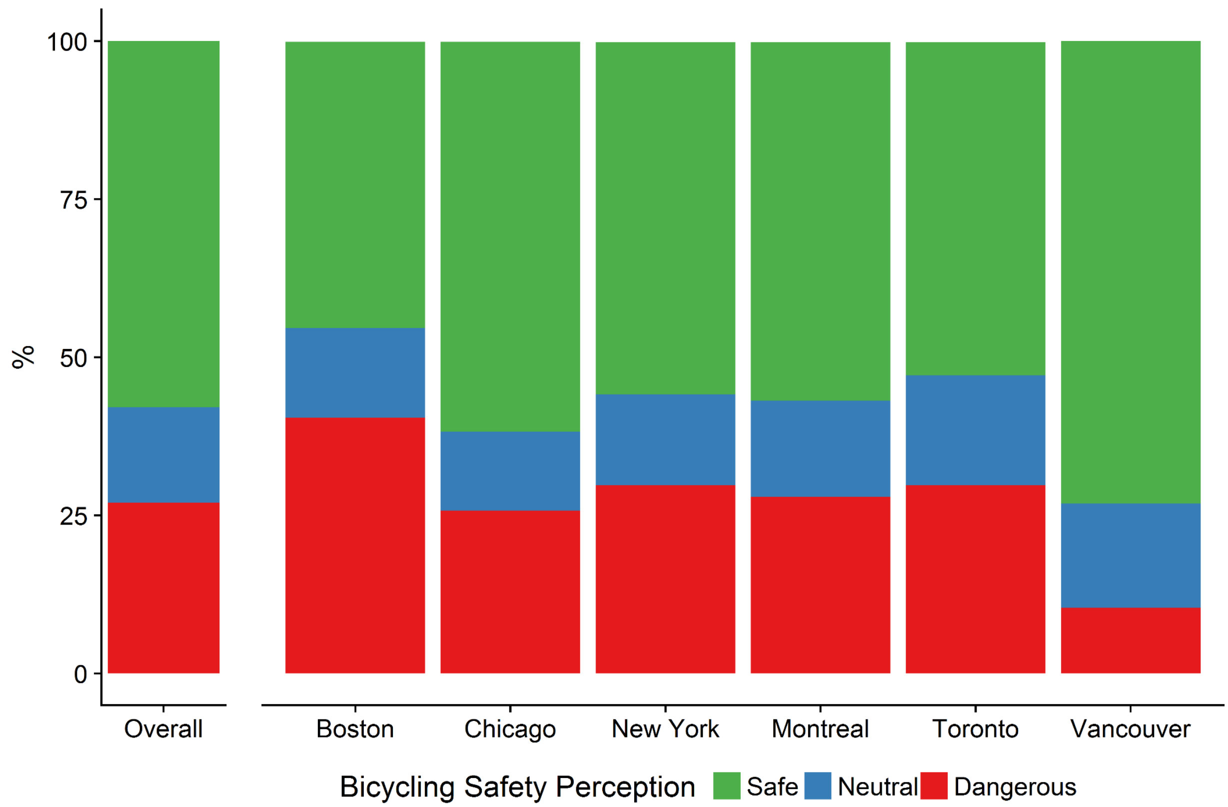

Figure 2: Weighted distribution of perceived bicycling safety, overall and by city.

3.2 Bicycling infrastructure and perceived bicycling safety

Within the six cities, bicycling infrastructure availability was significantly associated with the perceived safety of bicycling in that city (Table 3). For every 10-unit increase in Bike Lane Score the odds of rating bicycling as safe compared to neutral increased by 6% (OR = 1.06, 95% confidence interval (CI): 1.02 to 1.10), and the odds of rating bicycling as dangerous compared to neutral were estimated to increase by 4% (OR = 1.04, 95% CI: 1.00 to 1.08).

Variable	Outcome	Unadjusted OR[a] (95% CI)	Adjusted OR[b] (95% CI)
Residential Bike Lane Score			
	Safe	**1.05 (1.01, 1.09)**	**1.06 (1.02, 1.10)**
10 unit change	Neutral	Reference	
	Dangerous	**1.06 (1.02, 1.11)**	1.04 (1.00, 1.08)
Gender [ref=Female]			
	Safe	0.81 (0.63,1.03)	0.82 (0.64, 1.04)
Male	Neutral	Reference	
	Dangerous	**0.57 (0.43, 0.74)**	**0.57 (0.44, 0.74)**
Age			
	Safe	0.95 (0.85, 1.05)	0.94 (0.84, 1.04)
10 year change	Neutral	Reference	
	Dangerous	**1.29 (1.15, 1.44)**	**1.21 (1.08, 1.35)**
Income [ref=<50 K]			
50k – 100 K	Safe	0.94 (0.69, 1.28)	0.88 (0.64, 1.22)
	Neutral	Reference	

	Dangerous	**1.42 (1.01, 1.99)**	1.07 (0.75, 1.52)
	Safe	1.01 (0.73, 1.42)	0.88 (0.62, 1.26)
>100 K	Neutral	Reference	
	Dangerous	**1.84 (1.29, 2.62)**	1.21 (0.82, 1.78)
	Safe	**0.60 (0.38, 0.96)**	**0.57 (0.35, 0.93)**
Refuse	Neutral	Reference	
	Dangerous	0.82 (0.50, 1.36)	**0.54 (0.31, 0.92)**
Ethnicity [ref = White/Caucasian]			
	Safe	**0.68 (0.48, 0.97)**	**0.62 (0.44, 0.88)**
Asian / insular of the Pacific	Neutral	Reference	
	Dangerous	**0.42 (0.29, 0.62)**	**0.52 (0.35, 0.77)**
	Safe	0.74 (0.44, 1.24)	0.66 (0.38, 1.14)
Black/African/African-American	Neutral	Reference	
	Dangerous	**0.30 (0.16, 0.55)**	**0.36 (0.19, 0.68)**
	Safe	0.92 (0.54, 1.57)	0.78 (0.47, 1.31)
Hispanic/Latino/Spanish	Neutral	Reference	
	Dangerous	**0.33 (0.17, 0.63)**	**0.47 (0.24, 0.89)**
	Safe	1.24 (0.61, 2.54)	1.08 (0.51, 2.27)
Other	Neutral	Reference	
	Dangerous	1.02 (0.46, 2.24)	1.19 (0.52, 2.72)
Have Children Under 18 [ref = None]			
	Safe	**1.77 (1.34 2.35)**	**1.86 (1.40, 2.48)**
At least 1	Neutral	Reference	
	Dangerous	0.85 (0.63, 1.16)	0.99 (0.72, 1.36)
Education [ref = Highschool or Less			
	Safe	1.34 (0.87, 2.04)	1.38 (0.90, 2.12)
Post-Secondary	Neutral	Reference	
	Dangerous	**3.07 (1.85, 5.08)**	**2.43 (1.43, 4.10)**
Average Daily Bicycling in Previous Month			
	Safe	1.17 (0.94, 1.47)	1.18 (0.94, 1.47)
1 hour change	Neutral	Reference	
	Dangerous	**0.61 (0.46, 0.80)**	**0.67 (0.50, 0.90)**

[a] Unadjusted refers to a model consisting of the variables + City Term, [b] Adjusted refers to a model consisting of all variables + City Term; Bold: $p<0.05$

Table 3: Results of multinomial logistic regression models estimating associations between Bike Lane Score (proxy for spatial access to bicycle infrastructure around one's residence), sociodemographic characteristics, and perceived safety of bicycling among 3493 IBICCS respondents reporting having cycled in the previous month.

The marginal effects plot visualises the estimated relationship between bicycling infrastructure availability and perceived bicycling safety (Figure 3a). Model predictions indicate that with larger Bike Lane Score values, there is an increase in the predicted probability that the average bicyclist perceives bicycling as safe, a decrease in the probability they perceive bicycling to be neutral, and virtually no effect on the probability they perceive bicycling to be dangerous (Figure 3a).

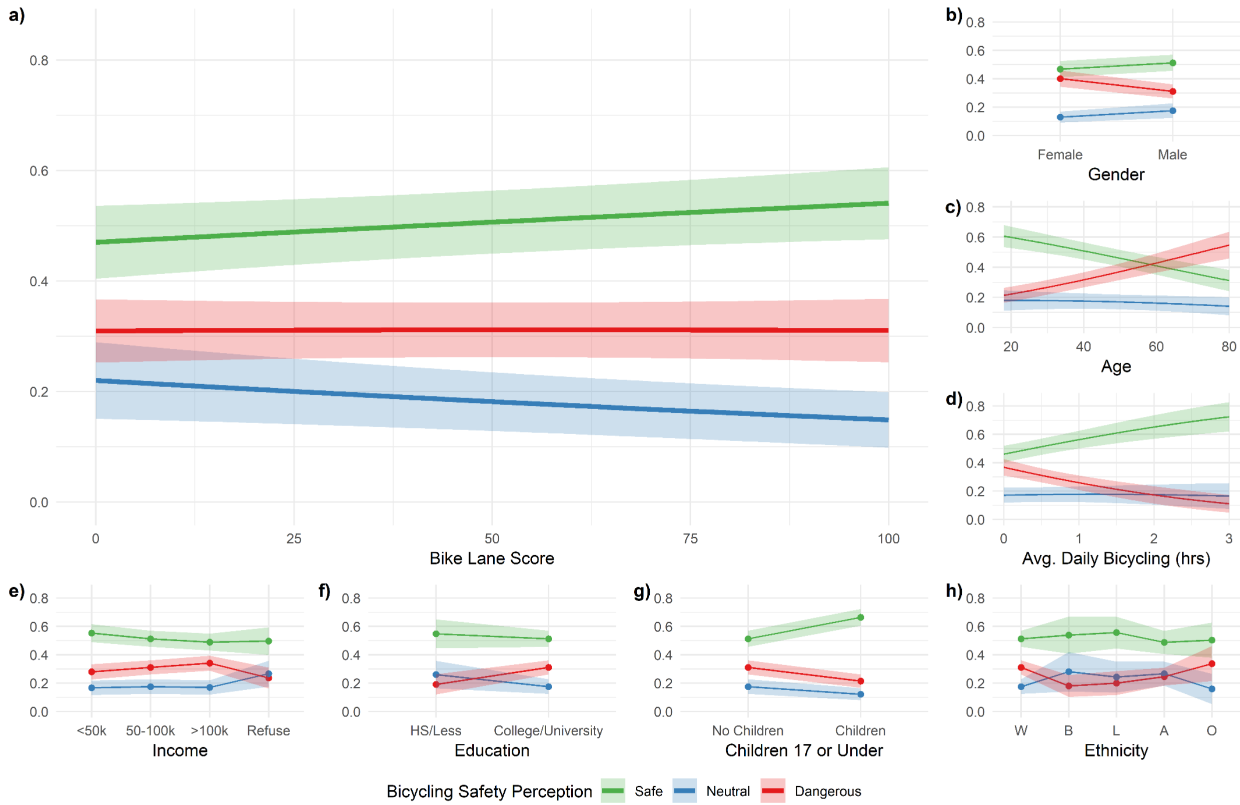

Figure 3: Marginal effects plots visualize the predicted probability that a bicyclist perceives bicycling in their city as safe, neutral, or dangerous across different values for each variable, when all other independent variables are held to their mean or mode. Each plot describes how the perception of bicycling safety would be expected to change given a particular variable's value was changed for bicyclists who, in all other aspects, are average with respect to sociodemographic characteristics within the sample. For example, in 3b) the average female bicyclist is less likely to rate bicycling as safe or neutral and more likely to rate bicycling as dangerous, when compared to the average male bicyclist. HS: High School education; W: White/Caucasian; B: Black/African/African-American; H: Hispanic/Latino/Spanish;A: Asian/insular of the Pacific; O: Other.

The predicted effect of increasing bicycling infrastructure availability for a hypothetical sample of bicyclists, such that the Bike Lane Score increases from 0 to 100, suggests that perceptions shifted from neutral to safe, but the perception of bicycling as dangerous was virtually unchanged (Figure 4). The hypothetical sample were, on average, 7.8% more likely to perceive bicycling as safe (predictions ranged between a 2.4% and 12.7% increase), 7.7% less likely to perceive bicycling as neutral (predictions ranged between a 2.0% and 13.0% decrease) and 0.1% less likely to perceive bicycling as dangerous (predictions ranged between 2.2% decrease and 3.1% increase).

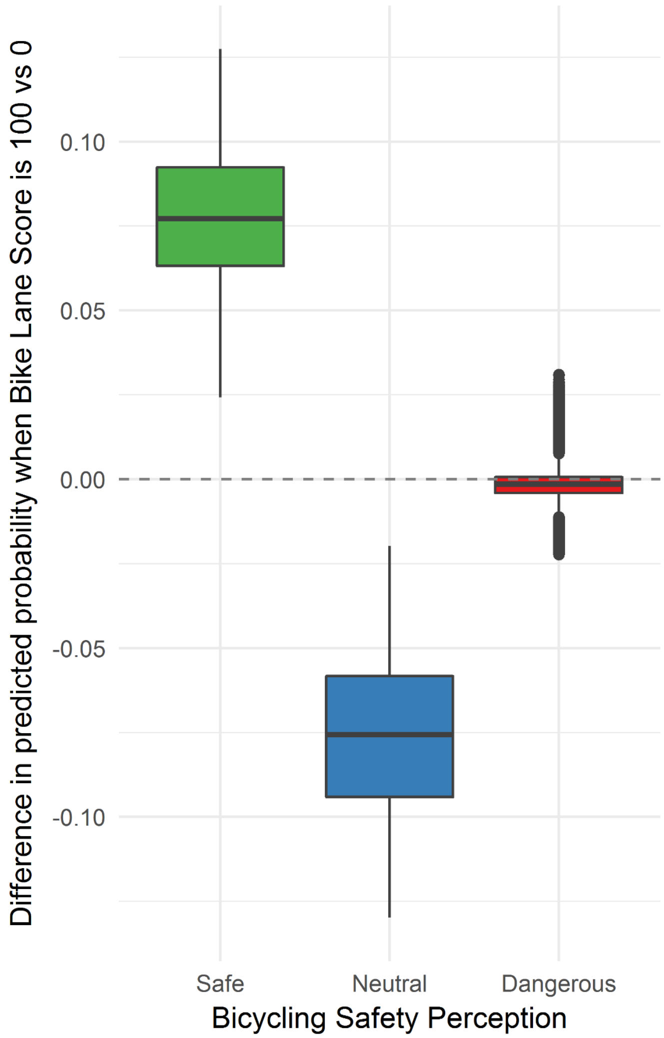

Figure 4: The distribution of the predicted change in probability of perceiving bicycling as safe, neutral and dangerous for a hypothetical sample of bicyclists when the bicycle infrastructure availability was increased such that the Bike Lane Score went from 0 to 100.

3.3 Sociodemographic characteristics and perceived bicycling safety

Adjusted models indicate that sociodemographic characteristics are statistically associated with bicycling safety perceptions (Table 3). Bicyclists who are male, younger, lower income, have young children, have a high-school education, and bicycle more frequently are predicted to be more likely to perceive bicycling in their city to be safe (Figure 3b-d, 3f-h). Ethnic background does not appear to be associated the likelihood with perceive bicycling as safe, but rather the likelihood that bicycling is rated neutral or dangerous, with non-Caucasian bicyclists being more likely to rate bicycling as neutral compared to dangerous (Figure 3e).

4.0 Discussion

In this study, we examined the association between perceived bicycling safety and spatial access to bicycle infrastructure accounting for sociodemographic characteristics, amongst over 3,000 bicyclists across 6 geographically diverse major Canadian and US cities, including Boston, Chicago, New York, Toronto, Montreal and Vancouver. These cities covered a wide range of bicycling conditions and safety contexts with mode share ranging from 0.8% to 4.4% of commuters who travel by bicycle (Statistics Canada, 2013c, 2013d, 2013b; US Census Bureau, 2017b), bicyclist fatality rates varying between 0.60 to 2.94 deaths per million bicycle trips (Urban Systems, 2015) and the proportion of bicyclists who perceive cycling to be safe between 45.3% to 73.2%. In multinomial regression analyses, bicycle infrastructure was positively associated with the likelihood of perceiving bicycling as safe compared to neutral. Bicyclists who are male, younger, lower income, have young children, have a high-school education, and bicycle are predicted to be more likely to perceive bicycling in their city to be safe. Our adjusted model indicated that increasing the availability of bicycling infrastructure such that the Bike Lane Score increased from 0 to 100, would result in a 7.8% average increase in the probability a bicyclist perceives bicycling to be safe. These results highlight that amongst a population that report bicycling, the availability of nearby bicycle infrastructure, in combination with individual sociodemographic characteristics, plays a role in shaping overall perceptions of bicycling safety.

Our findings support the hypothesis that bicycling infrastructure around one's residence is associated with more favourable perceptions of bicycling safety. The finding that greater availability is associated with a greater likelihood of rating bicycling as safe is consistent with previous research which suggests that at the network level, bicyclists perceive bicycle facilities to be safer than bicycling in mixed traffic (Manton et al., 2016; Møller and Hels, 2008; Parkin et al., 2007; Winters et al., 2012b). Bike Lane Score is a generalized metric of bicycling infrastructure availability, and thus our work complements this past work investigating how perceived safety varies for specific route characteristics (Manton et al., 2016; Møller and Hels, 2008; Parkin et al., 2007; Winters et al., 2012b). Our results show a positive relationship between availability of bicycle infrastructure around one's residence and perceiving bicycling as safe in one's city, but no difference in perceiving bicycling as dangerous. This result suggests that increasing the availability of bicycling facilities may lead to improved safety perceptions amongst those who feel neutral, but may not be effective way to improve perceptions of bicycling safety for those who already consider bicycling to be dangerous.

Implementing bicycle infrastructure may also be a means of promoting gender equity in a traditionally male dominated activity, at least in cities with low ridership levels (Aldred et al., 2016a; Garrard et al., 2008). In our sample, females are underrepresented as only 38.9% of bicyclists are female compared to 52.3% of participants in our full sample. The sex imbalances often found in bicycling populations within low bicycling contexts are often attributed to differences in risk aversion where women are more likely to perceive bicycling to be a risky mode of a transport and choose not to bicycle (Garrard et al., 2008; Heinen et al., 2010). Our research indicates that after controlling for confounders such as bicycling frequency, that there are still significant differences in perceptions of bicycling safety between males and females who already bicycle (at least once a week in the previous 30 days). Previous research has shown that female bicyclists, when compared to males, are more likely to perceive bicycling on specific routes to be too unsafe to bicycle on (Parkin et al., 2007), consider various situations while bicycling in traffic to be more risky (Bill et al., 2015; Chataway et al., 2014; Møller and Hels, 2008), and report that road segments along their commute are dangerous (Manton et al., 2016).

In cities where bicycling prevalence is low, not only do bicyclists tend to be disproportionately male, but they are also generally much younger (Aldred et al., 2016b). We find a similar pattern in our sample with participants over the age of 55 years make up only 19.0% of bicyclists but 30.4% of our full sample. Similar to that of the gendered trends, the literature suggests that older adults are underrepresented in low bicycling environments due to a higher aversion to bicycling in mixed traffic, combined with more limited physical abilities (Aldred et al., 2016b, 2016a). Our sample is limited only to those persons that already report bicycling, but still shows that younger bicyclists are still more likely to perceive bicycling as safe, compared to older bicyclists, even after controlling for bicycling regularity and the bicycling environment. Previous research has found mixed results on the associations between age and perceptions of bicycling safety within bicycling populations in Western Europe. Some research has indicated that older bicyclists are less likely to perceive bicycling as safe compared to their younger counterparts in Ireland and Denmark (Lawson et al., 2013; Møller and Hels, 2008), while others have found that older age was associated with an increased likelihood of perceiving bicycling as safe in Ireland and the UK (Manton et al., 2016; Parkin et al., 2007). We contribute to the literature in that we provide evidence that in a Canadian and US context, older bicyclists tend to perceive bicycling to be less safe than younger bicyclists.

Perceptions of safety may inform transportation choices (Aldred, 2016; Heinen et al., 2010), but safety perceptions don't necessarily align with observed safety (Winters et al., 2012a). We were not able to assess observed safety (e.g. a measure of injuries or crashes per unit of exposure), as spatially and temporally resolved crash data are not readily available across municipalities. At the city level, there is no correlation between the proportion of bicyclists who perceive bicycling to be dangerous in our sample and city-wide bicycling fatality rates. For example, Boston and Vancouver have similar bicyclist fatality rates, but Boston had the highest proportion reporting bicycling to be dangerous in our study, and Vancouver the lowest. Overall perceptions of bicycling safety are likely influenced not only by fatal and serious injuries that occur in a city, but also by minor injuries and near miss events which occur much more frequently and can be formative negative experiences (Aldred, 2016; Branion-Calles et al., 2017; Sanders, 2015).

Our study has various strengths and limitations. The IBICCS study provided a large sample of spatially located survey data over diverse contexts in six large Canadian and US cities, and used a standardized a measure of the bicycle environment, shown to be associated with bicycling (Winters et al., 2016). We also use an outcome with three levels to measure perceived safety (safe vs neutral vs dangerous), rather than a binary category (safe vs dangerous), which enables a more nuanced understanding of the association between access to bicycle infrastructure and perceived safety. Bike Lane Score is a standardized measure that captures the availability of bicycle infrastructure, and was the best available proxy for bicycle infrastructure consistent across cities at the time of the study. The development of Bike Score, including the weighting and decay functions, were informed by research but led by a private company. Bike Score uses a proprietary distance decay function to weight nearby infrastructure higher than distant infrastructure, but the score does not provide the distance to nearest infrastructure, a metric is often used in research studies (Panter et al., 2016). To note, the methodology of Bike Score has recently changed, and the description in this paper differs from the Redfin website (Walk Score, 2018). Motor vehicle traffic volumes may also play a role in safety perceptions (Parkin et al., 2007; Winters et al., 2012b), but standardized, spatially resolved data on traffic volumes was not available. Of note, the administrative city boundaries vary in terms of the geographic extent with some cities covering a much larger area (e.g., New York, Chicago). The IBICCS sample was an online panel survey, and both a large sample size and use of post-stratification weights on age and sex improve the generalizability of our results.

5.0 Conclusions

Our results show that within six major Canadian and US cities, greater availability of bicycle infrastructure as represented by the Bike Lane Score of a bicyclist's residence, is associated with greater odds of perceiving the broader city-wide bicycling environment as safe. We suggest that municipalities who wish to expand their bicycling network, thereby increasing spatial access to bicycle infrastructure, could see the perceived safety of bicycling in their city increase amongst bicyclists. These findings can be complemented by natural experiment studies which track changes in perceived safety as bicycle networks are expanded.

Competing interests

The authors have no financial or non-financial competing interests to declare.

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