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Research Article

Distractions or long waits? Impacts on risky crossing behaviour

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ABSTRACT

Pedestrian-vehicle conflicts at intersections are considered as a major source of injuries and fatalities. Intersections are a critical part of roadway design since pedestrians are exposed to different and potentially dangerous activities due to how an intersection is designed, but also what the pedestrian is doing and where in the city they are. In this study, various influences on risky crossing behaviour are examined. At the individual level, the influence of distractions and where people are looking before crossing are tested. Further, various intersection design variables including wait time, intersection size and speed limits, and contextual variables such as the built environment nearby and traffic flow are examined. The data was gathered by observing pedestrians at 24 intersections in Montreal and Quebec City (12 each). Logistic regression models were estimated to determine the influencing variables on four dangerous behaviours: a) start on red, b) finish on red, c) finish on red having started on green, and d) cross completely on red. Results demonstrate the importance of wait time on risky crossing behaviour with short wait times (< 30s) decreasing the likelihood of such behaviours considerably. For individual behaviour, having a cellphone in one's hand reduces the likelihood of starting to cross on red. In contrast, looking at traffic was over four times more associated with crossing illegally.

1. Introduction

Crash data reveal that numerous dangerous situations still exist for pedestrians as vulnerable road users, owing to the fact that cities were (and still are) primarily designed for vehicles for nearly a century [1–3]. In 2013, pedestrians represented 14 % of road crash fatalities reported in the US [4], and 17.3 % of road crash fatalities (332 people) in 2018 in Canada [5]. In Montreal, Canada, the majority (approximately 60 %) of vehicle–pedestrian collisions occur at intersections [6]. As such, intersections continue to be an important consideration for pedestrian's road safety.

Pedestrians are often insufficiently protected at intersections with preference typically given to vehicle movement in designing intersections and traffic signals programming. In this regard, numerous studies have demonstrated the significant impact of age and gender on pedestrian behaviour, with findings indicating that males exhibit a propensity for riskier road crossing behaviours compared to females, often attributed to shorter waiting times [7–9]. Additionally, models have been devised to analyze pedestrian crossing speeds and times, aiding in the design of appropriate crosswalk widths [10]. Moreover, research has underscored the effect of traffic volume, as well as environmental factors such as darkness and weather conditions, on pedestrian crossing behaviours [11]. Pedestrian crossing behaviours have been categorized into various types, including two-gap, risk-taking, two-stage, walk and look, single-stage, and rolling at different facilities [12]. Studies investigating pedestrian gap acceptance and critical gap have revealed that factors such as walking speed and road width play pivotal roles in determining whether pedestrians accept or reject gaps, typically allowing for a margin of 2 s between lag and gap [13,14].

Intersections can be busy and complex environments, making it essential for pedestrians to be fully focused and alert when crossing the road. However, distractions such as talking to friends, listening to music through headphones, or using a cell phone can easily divert pedestrians' attention away from their surroundings, potentially leading to risky crossing behaviour. Despite the potential impact of distractions on pedestrian safety at intersections, little is known about how these behaviours relate to risky crossing behaviour. Research in this area could provide valuable insights into the underlying factors that contribute to unsafe pedestrian behaviour at intersections and inform the development of interventions to improve pedestrian safety.

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Better knowledge of pedestrian safety can support walking, which is important for reducing greenhouse gas emissions, promoting good public health, ensuring access for everyone, and enhancing population well-being. To gain a new understanding of variables influencing crossing behaviour, this study used observational data from twelve intersections in each of Montreal and Quebec City, Canada.

1.1. Background

Various research has been conducted on pedestrians with respect to distractions. As a result of both the relative newness and impacts on attention, studies of mobile phone use have proliferated. In many cases, in order to create controlled studies, researchers have used experimental settings that limit danger such as virtual environments [15]. Such research finds that texting has a considerable impact on numerous behavioural measures and that using a cellphone increased the likelihood of being hit or having a near miss. The point that using a cellphone reduces one's attention to the surrounding environment is not in question. However, how the general public use cellphones at dangerous locations such as intersections is important to understand outside of artificial settings because people adjust their behaviour.

One issue of artificial experimental settings is that people are aware that they are being observed. Observational studies can be used to examine how people behave in the real world and are considered a reliable method to capture true behaviour [16]. In a systematic review of observational studies of the impact of mobile phone use on pedestrian behaviour, Yadav and Velaga [16] highlighted several short comings in the current literature: 1) although using a mobile phone is a distraction, the link with dangerous behaviour is unclear; 2) the studies have often been at limited locations (most only observe one intersection) and few consider different land-use environments; 3) studies do not consider intersection design most of the time; 4) signal characteristics are not considered. We would further add that few studies considered the general population including the elderly (exceptions include Escobar et al., [17]) and no studies examined behaviour over seasons. Important behaviour might change over seasons such as the likelihood of waiting to cross, especially in locations like Canada where winters are harsh. This study design will address all of those gaps.

Yadav and Velaga's systematic review [16] further highlighted several important points. Only 3 of the 39 studies had 20 or more intersections, with 29 having fewer than 10 so the ability to generalize and understand the impact of intersection design was significantly limited. Related to that as the variation would be too limited, few studies considered waiting time, only two considered the crossing length, few considered the number of lanes, only one considered the speed of approaching vehicles, and only a few considered traffic volumes. The authors also emphasized that the changes in behavioural patterns of pedestrians using mobile phones do not necessarily lead to increased safety risk as individuals' moderate what risks they will take. Pedestrian behaviour is likely to vary depending on the intersection design and the context, yet only a few studies considered those. For land use, Yadav and Velaga reported that 9 out of the 39 papers considered land use, but only 4 had more than 8 locations limiting the ability to control for both design and context. As such, a real lack of studies that are set up to control for those factors is evident concerning cellphone use as a distraction.

General pedestrian studies: Studies have shown that various factors influence crossing behaviour in general (without consideration of distractions). These factors include individual characteristics, intersection design, traffic volume, and other road user behaviours.

Individual characteristics: In terms of personal characteristics, some research has revealed that men are more likely than women to commit violations and cross on red [8,18,19]. For age, young adult pedestrians (aged 18–30) were found to commit more violations of traffic rules than other age groups, whereas senior pedestrians were shown to be less prone to engage in unsafe behaviour [20]. An additional human factor could relate to waiting tolerance. In some countries around the world such as China (Beijing), Ireland (Dublin), India (city of Kanpur), and France (Strasbourg) pedestrians who committed a violation had lower personal waiting-time thresholds Wang et al. [21].

Intersection design: These characteristics affect pedestrian violations such as crossing on red. The presence [22,23] and the design of the pedestrian signal itself have been shown to influence behaviour, with one study suggesting that a countdown display can minimize violations in specific situations [24]. One study demonstrated that waiting times at intersections influenced pedestrian decisions. For example, pedestrians were more likely to cross on red at intersections with long waiting times [25].

Road design can reduce risky pedestrian behaviours. Some examples include raised medians or pedestrian refuge islands [26]. Studies show that the length of crossing can influence risky behaviour: longer crossings were found to contribute to fewer violations [22,27], which may be related to the risk of being exposed to danger for longer. As well, the distance pedestrians must cross has a substantial effect on pedestrian speed with research demonstrating lengthier crossings resulted in pedestrians walking faster [28].

The context of the crossing can influence behaviour. The environment at intersections along with traffic conditions have a direct impact on pedestrian behaviour [29,30]. Kooij et al. [30] suggested three influences on a pedestrian's choice to cross a road or pause before crossing: the presence of oncoming cars, the pedestrian's awareness of them, and the spatial layout of the surrounding environment. Furthermore, Ukkusuri et al. [31] found that areas with a larger proportion of industrial, commercial, and open land-use categories had a higher risk of crashes, whereas the ones with a considerably larger residential land-use fraction had a lower risk of collisions.

Risky behaviours: Distractions such as using headphones or a cellphone could influence behaviour. Basch et al. [32] found that using headphones was the most common distraction for pedestrians in New York. They report that just over a quarter of pedestrians crossing on Walk had distracted behaviour (headphones, looking down, or talking on mobile). The percentages of distracted behaviour when crossing on Don't Walk was higher, representing 42 % of such behaviour. However, it is not clear from the study whether Don't Walk is flashing or steady. Wearing headphones could lower a person's capacity to hear or be aware of their surroundings and avoid vehicles that are causing danger (e.g., rushing a red light, or conducting a turn without properly looking for pedestrians). However, this could also be applied to people who are hard of hearing, such as older people, and the assumption of good hearing in design could create dangerous conditions [33]. However, it is not clear why waiting longer to cross would be considered risky. Thompson et al.'s [34] study found that people texting or talking on a mobile phone walked slower, as did people talking with a companion. However, they also found that people listening to music (again the most common distraction observed) crossed more quickly than others. Mohammed [35] measured speeds and found that average walking speeds were 5.14 ft./s (1.57 m/s) versus those with a phone at 4.53 ft./s 1.38 m/s. However, those speeds are both higher than the recommended pedestrian crossing speeds applied in traffic engineering (e.g., 1.2 m/s, 1.1 m/s) and are considerably higher than recommended elderly crossing speeds (e.g., 0.9 m/s or 0.8 m/s). Hatfield and Murphy [36] in observations of suburban Sydney intersections found that specifically females who were talking on a cellphone crossed slower. Walking slower is not a violation but could increase danger by exposing them for longer periods of time. This contrasts with the observation for headphone distraction. Nasar et al. [37] in a study of individuals on a university campus found that mobile phone users were more likely to cross while a car was approaching than those with no distraction, though they note that no car had to perform evasive maneuvers. It was not clear whether pedestrians are given priority on the campus or not. As mentioned, although individuals walked slower, their speeds were still higher than older populations and one should examine whether such distractions result in situations worse than vulnerable populations that should be planned for.

Those studies suggest that distractions such as mobiles or headphones might be associated with unsafe behaviours such as crossing on Don't Walk. However, people may also adjust their risky behaviour when conducting such activities that are considered distractions as they may be aware that their capacity to watch for dangerous vehicle behaviour is reduced [16]. Further, if a system is to accommodate people with different abilities, and not only those with all their senses (e.g., a system should not be built that would exclude people with hearing or visual impairments), then "distractions" that limit their mobility (e.g., slowing them down) should never be a legitimate reason for suffering a collision with a motorized vehicle.

Risky behaviour could also be linked to head movement. Hatfield and Murphy [36] found that women talking on cellphones were less likely to look at traffic before crossing which could be risky if a driver is wanting to cross the same space at the same time (legally or illegally). On the other hand, an individual checking traffic may be observing general traffic conditions, but they may also be looking for an opportunity to cross outside of the green traffic signal. Hashimoto et al. [29] assumed that pedestrians' intentions and actions vary in response to changing traffic conditions, such as turning their heads to face turning automobiles. Another example would be an individual looking at the ground (and not at the traffic), who may be doing so because they are not confident of their footing and fear falling [38].

Traffic volume: another element that might influence dangerous behaviour is traffic volume. Normally pedestrians do not tend to cross on red on streets with higher traffic volumes because of the danger imposed. Duduta, Zhang and Kroneberger [25] found that traffic volume was negatively associated with people crossing illegally. This means that higher traffic decreases the probability of crossing on red, again likely related to the situation being too dangerous. In addition, they found that gaps which provide a few seconds break in traffic could be a key predictor of the likelihood to cross on red.

Many individual and environmental characteristics can influence risky behaviour such as crossing on red. However, none of the mentioned field studies looked at all these characteristics concurrently and each of the referred studies considered only some of the aspects of the influence of these characteristics on risky crossing behaviour. Additionally, the gap in the study of pedestrian behaviour at intersections is the lack of information on how distractions and individual characteristics interact with the built environment to influence risky crossing behaviour.

Previous research has often examined the links between distractions and outcomes such as walking speed. Although past research has found that listening to headphones to be the most common distraction, the research did not examine whether it was associated with risky pedestrian behaviour. Talking (both on the phone and with a companion) was associated with walking slower, while listening to headphones was associated with walking faster [34]. Walking slower means that a person is in a conflict zone for longer which can be unsafe. Being distracted was associated with crossing on Don't Walk or simply crossing when there was an approaching vehicle (on a university campus). As such, there is some suggestion of a higher likelihood of risky behaviours. However, those studies were conducted some years ago and people may have adjusted their behaviour. In those studies, distinctions between age were not made either.

While some studies have suggested that men are more likely to cross on red than women and young adult pedestrians are more likely to engage in unsafe behaviour than older ones, there is limited research on how these individual characteristics interact with the built environment to influence risky crossing behaviour. The context within which people behave has an impact on their behaviour; people in more dangerous situations are likely to behave differently than they would in a safe one. For example, crossing 1 one lane on a traffic-calmed street with low traffic volumes while looking at a phone is more likely than if that same person was put at an intersection with 4 lanes of fast-moving traffic. Further to individual factors, little is known about how the built environment interacts with individual characteristics to influence risky pedestrian behaviours. Addressing these knowledge gaps could provide valuable insights into the underlying factors that contribute to unsafe pedestrian behaviour at intersections and inform the development of interventions to improve pedestrian safety.

The study aims to explore how a range of factors, including pedestrian characteristics, behaviour, and intersection attributes, influence risky crossing behaviour. Specifically, the research investigates the relationship between pedestrian demographics (age and gender), behaviour patterns (such as head movements and distractions like headphone use or cellphone usage), and various intersection features (such as waiting time, presence of street amenities, and lane configurations) on instances of risky crossing behaviour. These behaviours encompass starting to cross on red, finishing the crossing on red, starting on green and finishing on red, and crossing against the signal altogether. By examining the factors that contribute to risky crossing, this study aims to shed light on the underlying reasons for this risky behaviour and inform the development of targeted interventions to improve pedestrian safety. Additionally, the findings of this study may have broader implications for pedestrian safety at intersections, providing valuable insights into the factors that contribute to unsafe pedestrian behaviour and informing the development of effective interventions to improve pedestrian safety.

2. Methodology

2.1. Observation locations

The data for our observations was collected from two cities: Montreal and Quebec City. For each city, we selected twelve traffic-light-controlled intersections (Fig. 1) based on their geometric characteristics and the surrounding built environment (see Table 1). Techniques exist such as eye tracking [39,40] that allow researchers to see where individuals are looking and how much attention they are paying to different directions. However, in our case, the behaviours that we wish to observe such as distractions and head movement would likely be affected if the participants are aware of being observed. As such, a natural experimental setting was preferred.

In 2016, the city of Montreal covered an area of 366 km^2 and had a population of 1.7 million, which represented 40 % of the population of the census metropolitan area. Quebec City covered an area of 428 km^2 and had a population of 532,000 [41].

Geometric characteristics and the surrounding built environment had an important role in selecting intersections in both cities. The contextual information on the built environment and traffic were obtained from various sources including city officials. The most recent available counts of vehicles and pedestrian volume at the same time of day as the observations were obtained from the open access dataset [42] for Montreal and directly from the transport engineering department for Quebec City.

Nine characteristics of the intersections were observed including: waiting time, presence of street parking, bike lanes, refuge island, number of lanes, street crossing distance, presence of bus stops, and small refuge islands (Table 1). Due to high correlation between Street distance and Number of lanes (0.92, $p < 0.001$), only Number of lanes was retained in the analysis model because its explanatory power had a larger impact on the model. The Number of lanes was also highly correlated with the vehicle volume (0.83, $p < 0.001$) and so vehicle volume was dropped. Finally, the vehicle traffic and the Street distance are also highly correlated (0.80, $p < 0.001$), so the Number of lanes was the preferred variable.

The built environment was also categorized into three groups (Table 2) by Non-hierarchical analysis method (K-means cluster analysis) based on the presence of variables in a 500-m buffer zone around intersections: population density, material and social deprivation index

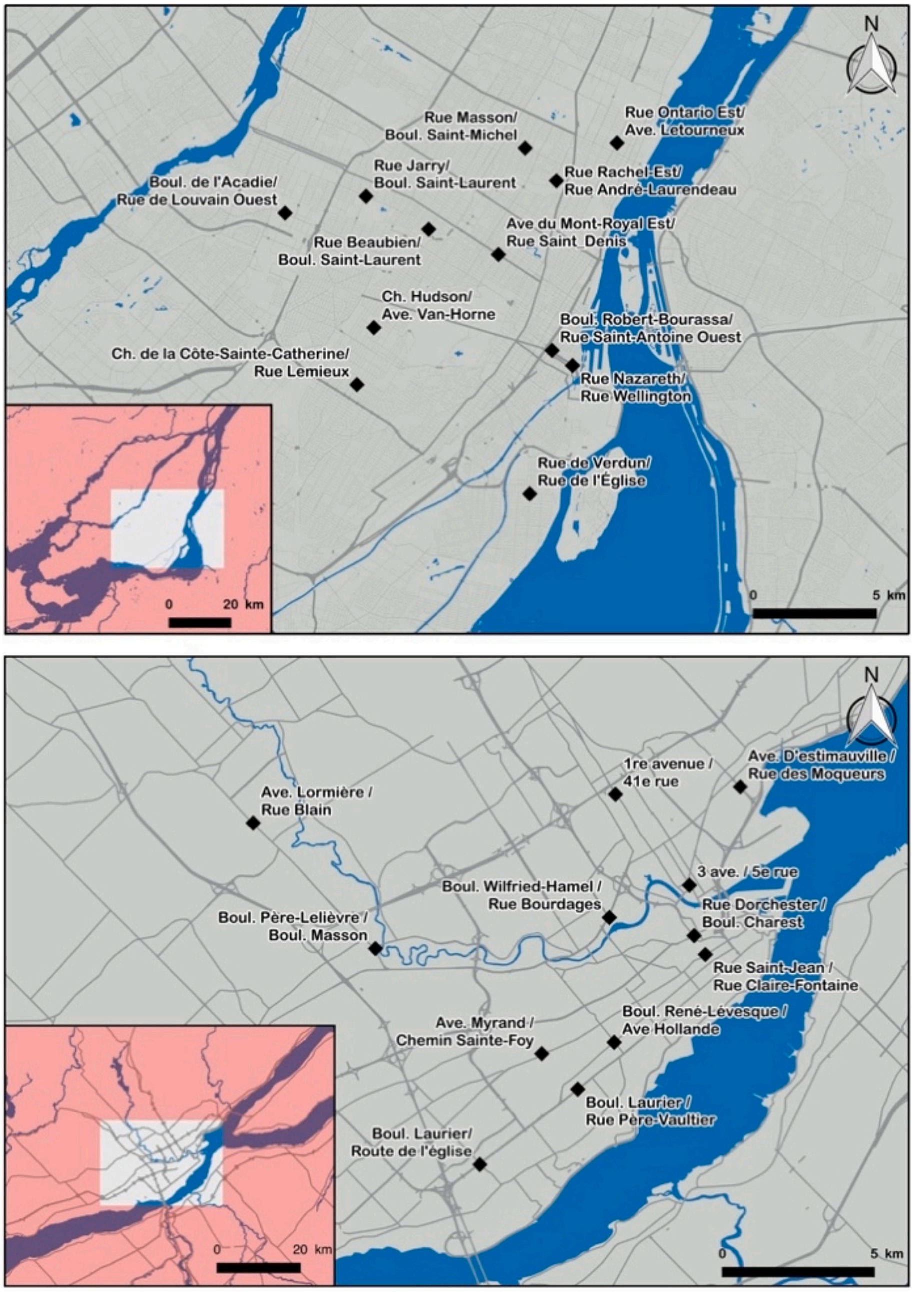


Fig. 1. The intersections location in Montreal (top) and Quebec City (bottom) (Rue = street; Boul. = boulevard). Image credit: Simon Turcotte.

[43], and the proportion of the buffer being a) residential, commercial, industrial or institutional land use [44]. Population density is used for two reasons: it is related to levels of walking; it is a proxy for the number of people who might be traveling in that area. Land-use mix is also related to travel modes. The material deprivation index "involves deprivation of the goods and conveniences that are part of modern life, such as adequate housing, possession of a car, access to high-speed internet, or a neighborhood with recreational areas" while the social deprivation index "is characterized by individuals living alone, being a lone parent and being separated, divorced or widowed" [43]. Both social and material deprivation can be used to consider questions of equity. Material deprivation includes measures such as car ownership and general wealth which are related to travel modes. Social deprivation was primarily used as a measure of equity, though studies have also found that walking levels can be higher for single parent households. The purpose of this was to ensure that a variety of contexts could be observed so that the influence of contextual differences could be minimized.

In terms of traffic, the most recent available counts of pedestrian volume at the same time of day as the observations were obtained from the open access dataset for Montreal [45] and directly from the transport engineering department for Quebec City. In addition, the legal posted speed limits were included.

Pedestrian Signal Management Montreal vs *Quebec:* With respect to pedestrian phases at traffic-light-controlled intersections, Montreal and Quebec City have different management systems (see Table 3). While the Ministry of Transportation of Quebec issues universal rules across the province of Quebec for pedestrian lights (white silhouette, flashing hand, etc.), municipalities are responsible for how these systems are integrated with automobile traffic. Quebec City uses a "protected mode" also known as "exclusive phasing" or "all-red" [46]. However, it is not a true protected phase as the City allows vehicles to turn right on red at most intersections. As well, nearly all pedestrian phases are integrated at

Table 1
Intersections observed in Montreal and Quebec.

Intersection name	Number of lanes	Street dist.	Refuge island	Intersection type	Street parking	Number of Bus stop	Bike lane	Pedestrian volume	Vehicle volume	Average waiting time (respect lights)	Built environment type
MONTREAL											
Beaubien & Saint Laurent	3 and 4	10 & 14 m	0	T type (three ways)	yes	2	no	2146	775	99 s	Most urban
Jarry & Saint Laurent	5 and 7	17 & 23 m	1.5 m	four ways	yes	4	no	4811	14,952	25 s	Middle density urban
Acadie & Louvain	4 and 7	14 & 26 m	1.5 m	four ways	no	2	no	349	14,591	39 s	Most residential
Rachel & Laurendeau	3 and 5	19 & 17 m	0	four ways	yes	3	yes	995	5067	49 s	Middle density urban
Cote Saint Catherin & Lemieux	6 and 6	16 & 13 m	0	T type (three ways)	yes	2	no	517	4904	15 s	Most urban
Hudson & Van Horne	4 and 3	16 & 11 m	0	four ways	yes	2	no	661	5145	23 s	Most urban
Verdun & De L'Église	3 and 3	12 & 10 m	0	four ways	yes	3	no	1026	4209	18 s	Most urban
Nazareth & Wellington	2 and 5	17 & 18 m	0	four ways	no	1	no	1892	15,583	48 s	Middle density urban
Robert Bourassa & Saint Antoine	8 and 6	31 & 22 m	3 m	four ways	no	1	no	8354	15,623	39 s	Most urban
Mont Royal & Saint Denis	3 and 6	11 & 18 m	0	four ways	yes	4	no	6779	13,106	20s	Most urban
Ontario & Letourneux	4 and 4	12 & 12 m	0	four ways	yes	2	no	2040	3485	7 s	Most urban
Masson & Saint Michel	4 and 6	11 & 18 m	0	four ways	yes	4	no	2533	9135	35 s	Most urban
QUEBEC CITY											
3 me Avenue & 5 me Rue	2 and 4	7 & 10 m	0	four ways	yes	2	yes	725	4060	10s	Middle density urban
Dorchester & Charest	6 and 4	20 & 12 m	0	four ways	no	3	no	2379	13,226	43 s	Most urban
L'Ormiere & Blain	4 and 4	15 &15 m	0	four ways	no	2	yes	121	9152	46 s	Middle density urban
Pére Leliévre & Masson	4 and 4	12 & 12 m	0	four ways	no	0	yes	160	8346	39 s	Most residential
René Lévesque & Hollande	4 and 4	14 & 12 m	0	four ways	yes	2	no	718	7371	NS**	Most residential
Saint Jean & Claire Fontaine	2 and 3	6 & 9 m	0	T type (three ways)	no	1	no	530	2171	63 s	Middle density urban
Wilfried Hamel & Bourdages	8 and 4	33 & 15 m	3.5 m	four ways	no	2	no	473	16,372	54 s	Most urban
Laurier & De L'Église	8 and 4	28 & 14 m	2 m	four ways	no	3	no	965	23,960	47 s	Most residential
Myrand &Chemin Sainte Foy	4 and 4	12 & 15 m	0	four ways	no	2	no	537	6354	43 s	Most residential
1re Avenue & 41me Rue	4 and 5	14 & 19 m	0	four ways	no	4	no	1663	9970	68 s	Middle density urban
D'Estimauville & Des Moqueurs	2 and 4	8 & 18 m	0	four ways	no	1	no	4275	330	99 s	Middle density urban
Cartier & Grande Allée*	2 and 4	8 &13 m	0	four ways	no	2	no				Middle density urban
Laurier & Du Père Vaultier	4 and 2	24 & 9 m	0	T type (three ways)	no	2	no	112	10,064	36 s	Most residential

* This intersection was observed only in the Fall of 2019 and Spring of 2020 as it replaced another intersection where insufficient number of pedestrians were observed in the Summer of 2019.
** No pedestrians were observed to wait until the green at this intersection.

the end of the traffic cycle by call buttons. Finally, although it is an all-red system for vehicles, it is illegal for pedestrians to cross diagonally (though in practice many do). In Montreal, some intersections give pedestrians a few seconds to begin crossing before permitting vehicle movements, called the lead-pedestrian interval (LPI) [47]. Right turns on red are forbidden on the Island of Montreal and most pedestrian phases occur automatically. One final difference between the cities is the assumption of pedestrian speed. Montreal uses 1.1 m/s and in certain locations, reduces it to 1.0 m/s or 0.9 near schools, retirement homes, medical clinics, or hospitals. In Montreal, as the pedestrians cross concurrently with the traffic, they have more than the minimum time necessary to cross in many cases. Quebec City broadly uses 1.2 m/s and, as it is a pedestrian-only phase, the given number of seconds is based on the minimum time needed to cross at this speed, excluding the time necessary to cross diagonally. In certain cases, the timing may be extended due to complaints from citizens. Finally, both cities have upgraded most of their pedestrian traffic signals to use pedestrian countdowns which have been shown to improve safety behaviour [24].

Table 2
Built environment categories and their characteristics.

	Most urban Mean (Std. Dev.)	Middle density urban Mean (Std. Dev.)	Most residential Mean (Std. Dev.)
Population density	20,490 (2680)	11,742 (813)	6680 (1177)
Material deprivation index	−0.02 (0.03)	−0.04 (0.03)	0.00 (0.03)
Social deprivation index	0.05 (0.01)	0.04 (0.01)	0.02 (−0.02)
% Residential and commercial land use in buffer zone	35 % (0.11)	32 % (0.08)	38 % (0.06)
% Industrial and institutional land use in buffer zone*	7 % (0.03)	7 % (0.07)	7 % (0.03)

* This variable is not statistically different between the groups.

Table 3
Comparison of Pedestrian Signal Management Systems between Montreal and Quebec City.

Aspect	Montréal	Quebec
Management System	Lead-pedestrian interval (LPI), automatic pedestrian phases	"Protected mode" or "exclusive phasing" either automatic or with call buttons for pedestrian phases
Right Turn on Red Policy	Forbidden	Allowed at some intersections
Integration of Pedestrian Phases	Mostly automatic; some intersections have call buttons	Pedestrian phases integrated at the end of the traffic cycle by call buttons
Diagonal Crossing Policy	Not explicitly illegal, but not encouraged	Illegal, except where marking is explicit
Assumption of Pedestrian Speed	1.1 m/s (reduced to 1.0 m/s or 0.9 m/s in certain areas)	Broadly uses 1.2 m/s; timing based on minimum crossing time, excluding diagonal crossing
Timing Adjustment	Pedestrians cross concurrently with traffic, often with more time than minimum required	Timing based on minimum crossing time; may be extended based on complaints from citizens
Pedestrian Countdown Signals	Upgraded for improved safety behaviour	Upgraded for improved safety behaviour

2.2. Data collection: observation protocol and variables

Sample selection: The data was collected from 24 intersections through a systematic random selection of pedestrians crossing towards the observers. Pedestrians were selected as they approached the intersection, while they waited, and while they crossed. It was also possible to determine if they were traveling with someone, as opposed to just randomly standing next to a person at the intersection.

Data collection period: Observation periods were conducted at different times throughout the year, with each observation lasting for 3 h. During the summer of 2019, the 24 intersections were observed three times (morning, noon, and evening), totalling 9 h of observation and accounting for more than half of the project's total observations. In the fall of 2019 and spring of 2020 (each representing about 1/4 of the observations), observations were made at the end of the afternoon, from 3 p.m. to 6 p.m., as this is the period of the day when most collisions occur [29]. However, observations were not conducted in the winter of 2020 due to Covid-19 pandemic lockdown measures in Quebec [31].

Data collection procedure: Observations of pedestrian behaviours were done using a previously validated method [47,49], which divides pedestrian crossings into four "zones". Each of them refers to a specific moment in space and time and to specific variables to observe (Fig. 2). The fours zones are:

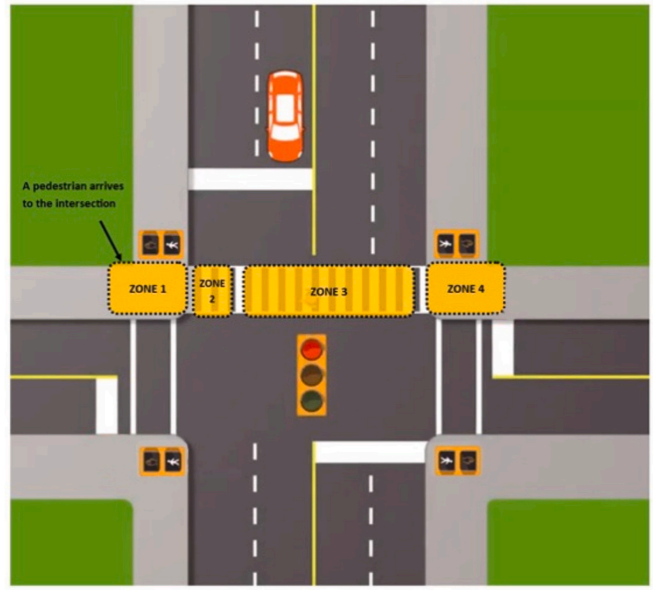


Fig. 2. Observations of pedestrian behaviours based on each zone.

- Zone 1: approaching the crossing,
- Zone 2: at the beginning of the crossing (as soon as one foot in on the street),
- Zone 3: at mid-crossing, and
- Zone 4: at the end of the crossing (when the last foot is out of the street).

Nearly all measures used in this study were observed in Zone 1 with the exception of the pedestrian light when the pedestrian started crossing (Zone 2) and the pedestrian light when they reach the other side (Zone 4). Additional details on observation protocol and practice can be found in [47,49]. Waiting time was observed using a separate protocol where a pedestrian is randomly chosen, and the time spent waiting within the intersection (at 1 or 2 corners depending on their crossings) is recorded (Fig. 3). Pedestrian characteristics and behaviours were recorded by a team of students (4, 2 in each city) without interviewing the pedestrians, so some errors in terms of gender or age group may have

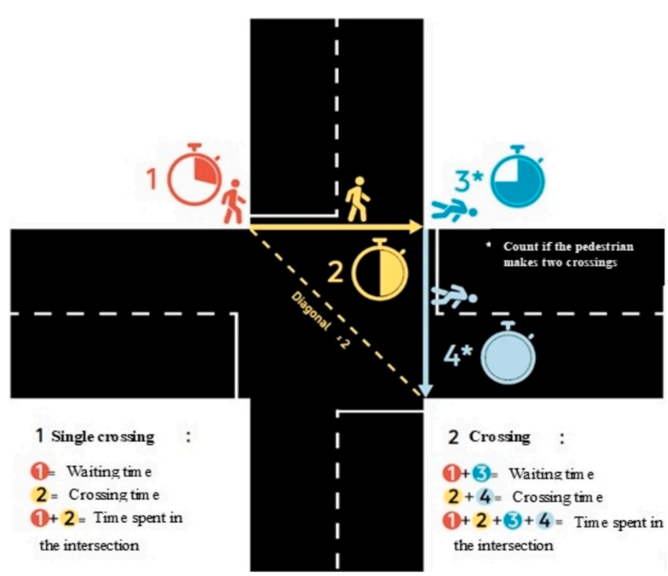


Fig. 3. Diagram of the methodology for calculating waiting times, crossing time, and time spent in the intersection.

occurred. The students received training prior to the main observation, and during the pilot observation, the inter-rater reliability of the observers was assessed.

2.3. Individual variables

Pedestrian characteristics: a selected sample population were observed and categorized based on gender and age. The inter-rater reliability of these classifications was confirmed before the main observations.

Pedestrian behaviours: head movements, including looking at traffic signals, traffic, the ground, other pedestrians, or electronic devices, were observed. Distractions were classified into four groups based on whether pedestrians were wearing headphones, were with someone, had a cellphone in hand, or were talking on the phone. The head movements and distractions of the pedestrians were observed before and during crossing.

Dangerous crossing behaviours: Risky behaviours of participants were classified into four categories as: 1) start crossing on red (or steady red hand), 2) finish on red (or steady red hand), 3) finish on red having started on green (or white silhouette), and 4) start and finish on red (or steady red hand) (see Table 4).

2.4. Statistical analyses

A total of 4711 pedestrian observations were conducted at 24 intersections in Montreal and Quebec cities. The frequency and percentage of participant characteristics, including their gender and age, were described for each city. Additionally, the percentage of pedestrians' distractions and head movements before crossing were reported in each city. The average waiting time and crossing violations were also described for both cities. STATA v.14.2 was used to examine all the mentioned variables and to check for significant differences between the two cities. Furthermore, logistic regression models were conducted to examine the likelihood of four different dangerous crossing behaviours, namely: 1) starting to cross on red (or red hand), 2) finishing the crossing on red (or red hand), 3) finishing the crossing on red after starting on green (or white silhouette), and 4) starting and finishing the crossing on red (or red hand) with pedestrian characteristics, behaviour (distractions and head movement), intersection characteristics, and context were taken into account in the analysis.

3. Results

3.1. Descriptive statistics

There were 4711 pedestrian observations in this dataset. The descriptive statistics of the observations are shown in Table 5. Some

Table 4
Dangerous crossing behaviours.

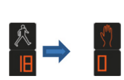
Dependent variables	Description	Visualization of a pedestrian light
Start on red	Pedestrians start crossing when the traffic light is red or a steady red hand (indicates that pedestrians may not cross).	
Finish on red	Pedestrians finish crossing when the traffic light is red or a steady red hand.	
Start on green and finish on red	Pedestrians start crossing when the traffic light is green or white silhouette then finish crossing on red or steady red hand.	
Cross on red	Pedestrians start and finish crossing when the traffic light is red or steady red hand.	

Table 5
Descriptive statistics ($n = 4711$ observations).

Variables	Montreal	Quebec
Observations	52 % (2446)	48 % (2265)
Female	52.3 % (1279)	50.3 % (1140) *
Age groups		
Children (roughly under 12)	2.4 % [59]	0.4 % [8] *
Teenager and young adults (roughly 13–24)	22 % (534)	24.6 % (557) *
Adults (roughly 25–64)	65 % (1578)	63 % (1430) *
Seniors (roughly 65 +)	11.3 % (276)	12 % (270)
Distraction before crossing		
Using headphones	17 %	15 %
Being with someone	14 %	16 % *
Cellphone in hand	13 %	12 %
Talking on a cellphone	3 %	2 %
Head movements before crossing		
Looking straight at traffic signal	85 %	57 % *
Looking at traffic	37 %	47 % *
Looking at the ground	20 %	18 %
Looking at other pedestrians	6 %	5 %
Looking at electronic device	6 %	3.50 %
Waiting time		
Average waiting time	28 s	30 s
Average waiting time, obey signals	33 s	45 s *
Crossing violation		
Start on red	8 %	29 % *
Finish on red	12 %	32 % *
Start on green finish on red	9 %	8 %
Cross on red (start and finish on red)	4 %	26 % *

* Statistical difference between cities at $p < 0.05$.

differences can be observed between the two cities. First, the crossing violations are all much higher in Quebec City than in Montreal. More women and children were observed in Montreal (as a share of total observations). No statistical differences in distractions were observed except for being with someone which was higher in Quebec City. For head movements, the percentage of people looking at the traffic signal before crossing is greater in Montreal. In contrast, pedestrians in Quebec City tended to look at traffic and the ground more. Other head movements were not significantly different between the two cities.

The average wait time at intersections is approximately 30 s in both cities, but this includes people who cross illegally (and do not wait the full time). The difference in average waiting time for those who respect the traffic signal is statistically significant. In Montreal pedestrians wait an average of 33 s while in Quebec City, this time goes up to around 45 s.

3.2. Dangerous crossing behaviours

The results of the logistic regression are summarized in Table 6.

Individual characteristics had some effects, but not on all measures. Results show that males are more likely to start and finish on red than females. For starting on red, we see that only children are many times less likely to do so than older people. However, when it comes to finishing on red having started on a green light, older pedestrians are many times more likely than other adults (odds ratios of 4.8 versus teenagers/young adults and 3.7 versus adults).

Various head movement measures were significant for three of the four outcomes. Looking at the traffic signal before crossing is statistically associated with being less likely to start, finish and cross on red. In contrast, looking at traffic before crossing was associated with being more likely to start, finish and cross on red. Results show that pedestrians who look at the ground or at other pedestrians were less likely to start and finish on red.

Table 6
Binary logistic regression of dangerous crossing behaviour.

Variables	Start on red	Finish on red	Finish on red, having started on green	Cross on red (start & finish on red)
	Odds ratio	Odds ratio	Odds ratio	Odds ratio
Age				
Children (under 12)	0.07*	NS	–	NS
Teenager and young adults [13–24]	NS	NS	0.21***	NS
Adults [25–64]	NS	NS	0.27***	NS
Seniors (65 +) (ref.)	1	1	1	1
Sex				
Female (ref.)	1	1	1	1
Male	1.27*	1.21*	NS	NS
Head movement (before crossing; non-exclusive categories)				
Looking at traffic signal	0.39***	0.53***	NS	0.37***
Looking at traffic	5.74***	2.02***	NS	5.13***
Looking at the ground	0.42***	0.53***	NS	0.56**
Looking at other pedestrians	0.48*	0.44***	NS	NS
Looking at electronic device	NS	NS	NS	NS
Distractions (before crossing; non-exclusive categories)				
Using headphones	NS	NS	0.37*	NS
Being with someone	0.66*	NS	NS	NS
Cellphone in hand	0.62*	NS	NS	0.56*
Talking on phone	NS	NS	NS	NS
Cross diagonally	NS	2.26*	22.38***	NS
Number of lanes				
3	21.32***	5.45***	NS	3.67***
4 (Ref)	1	1	1	1
5	0.39***	NS	NS	NS
6	0.44***	NS	NS	0.23***
7	0.07***	NS	NS	NS
8	0.01***	NS	NS	NS
Streets with speeds 40 km/h or less	1.67**	1.87***	NS	2.28***
Short ped. Wait time (< 30 s)	0.26***	0.36***	NS	0.09***
Refuge island	38.54***	4.82**	NS	6.41***
Car parking lanes	4.51***	NS	NS	3.03**
Bike lanes	NS	NS	NS	1.95***
Pedestrian traffic volume (1000s)	1.69***	NS	NS	NS
Built environment categories				
Most urban (ref.)	1	1	1	1
Middle density urban	1.83*	NS	NS	NS
Most residential	NS	NS	NS	0.04***
City				
Montreal (ref.)	1	1	1	1
Quebec	15.37***	3.05***	27.59***	21.13***
Season				
Summer (ref.)	1	1	1	1
Fall	NS	0.78*	NS	NS
Spring	2.54***	1.46**	NS	2.97***
Constant	0***	0.06***	0***	0.01***
N	4351	4351	2367	4351
R2	0.377	0.203	0.159	0.428

* $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.
NS: Not Significant.

The results of all types of distraction illustrate that they were statistically associated with risky behaviour: pedestrians who use headphone are less likely to finish on red having started on green. Previous studies had found that listening to headphone was associated with higher walking speeds [34]. Pedestrians who have a companion are less likely to start on red, while pedestrians who have a cellphone in hand are less likely to start on red and cross completely on red.

The finding shows that pedestrians crossing diagonally are more likely to finish on red having started on green, which is not surprising as the phase timing is not designed for these longer distances in Quebec.

For intersection characteristics, when the waiting time was short (less than 30 s), pedestrians are 3.8 times less likely to start on red, 2.7times less likely to finish on red, and 10 times less likely to cross on red. In a street with parking lanes, pedestrians are more likely to start, finish, and cross completely on red. Furthermore, the existence of a bike lane was not statistically associated with risky behaviour with one exception, pedestrians who cross completely on red (start & finish on red). The number of lanes is related to the size of intersections and the crossing distance was excluded. As the number of lanes increased, risky behaviours by pedestrians were generally observed to decrease in a logical manner for starting on red and crossing on red. This is likely related to a situation of too much danger. Vehicle traffic was not significant, however it is highly correlated to the number of lanes (>0.83, $p < 0.001$). In a separate analysis, vehicle traffic volume was tested without Number of lanes or Street distance (both highly correlated). Confirming the results shown for Number of lanes, an increase in traffic volume was associated with a decrease in all risky crossing behaviours except for starting on green and finishing on red.

Two measures were used for traffic characteristics: speed and volume. Lower speed limits were associated with more instances of start, finish, and crossing completely on red. The odds ratio for pedestrian traffic volume shows that as pedestrian numbers grow, they are more likely to start crossing on red. The number of lanes acts as a proxy for vehicle volume and as stated above, as the number of lanes increases, there is a significant decrease in the likelihood of all risky behaviours except for finishing on red having started on green. In a separate analysis (not shown here), the street crossing distance was tested in place of the Number of lanes. Consistent results are found with an increase in the crossing distance being associated with a decrease in the risky behaviours except for starting on green and finishing on red.

The built environment categories were statistically different before traffic and intersection design characteristics were included which suggests that the context may be less important than the design, though the pedestrian and traffic volumes are likely related to the built environment. Pedestrians in the most residential areas had an odds ratio of 0.07 compared to pedestrians in the most urban category.

All risky behaviours were more common in Quebec City than in Montreal: 15.4 times more likely to start on red, 2.9 times more likely to finish on red, 27.6 time more likely to cross on red (start and finish), and 21.3 more likely to finish on red having started on green.

Seasonal differences were observed, though some caution must be taken for the Spring results as this was when the Covid-19 pandemic significantly reduced traffic [50]. Pedestrians were 1.3 times less likely to finish on red in the Fall than they were in the Summer of 2019. There was no significant effect for the other measures when considering those two seasons only. For the Covid-19 Spring, pedestrians were more likely to start, finish and cross on red than the prior seasons, probably due to lower vehicle traffic.

4. Discussion

This study examined individual, intersection, and contextual influences on four risky crossing behaviours by pedestrians, all related to traffic signals compliance. As highlighted in the systematic review by Yadav and Velaga of cellphone use by pedestrians, a number of limitations existed with previous research on that topic that this research addressed: 1) although using a mobile phone is a distraction, the link with dangerous behaviour is unclear; 2) previous studies have often been at limited locations (most only observe one intersection) and few consider different land-use environments; 3) studies do not consider intersection design most of the time; 4) signal characteristics are not considered. In addition, few studies considered the general population including elderly (exceptions include [17] and no studies examined behaviour over seasons. The major point of our research is highlighted here with comparison to existing research where possible.

4.1. General behavioural results

First, our results related to individual characteristics such as gender and age group are consisted with previous findings, which indicate that males cross on the "Don't walk" sign more frequently [51]. Having started on green and finishing on red is a critical design problem as it shows that the amount of time given is insufficient. We found that seniors were more likely to have finished on red having started on green along with those who were crossing diagonal (Québec City almost exclusively uses a pedestrian only phase). Previous research found that seniors are more likely to finish on red [38], probably due to their slower walking speed. Escobar et al. found that individuals using cellphones had slower walking speeds than able bodied adults without distractions, but were still faster than older people. Yadav and Velaga's review [16] found mixed results for gender (though the major found that men were riskier). Individuals with headphones were less likely to finish on red having started on green which could be linked to previous findings that found that their walking speeds were higher [34].

Our study found that turning towards traffic was associated with illegal crossings. Aghabayk et al. [50] also found that looking at traffic relates to searching for a gap to cross, no matter the traffic signal. The same hypothesis stands in the present study. Two studies in Taiwan found a relationship between cellphone use and lower head turn frequency [52]. Although turning to check traffic is good practice to be aware of traffic danger, traffic engineers and traffic safety approaches should work to reduce the need for the victim to be constantly vigilant and such improvements would help those that are visually impaired and elderly who find it hard to look in different directions while walking.

Once the refuge island was taken into account, our results for the large intersections are consistent with Duduta et al. [25] who found that the length of crosswalks was negatively related to the likelihood of crossing on red (number of lanes in our study).

As for the waiting time, a direct consequence of traffic signal programming, our results reflect what is highlighted in the *Highway Capacity Manual* (HCM), namely that pedestrians are extremely likely to cross on red if there is a wait-time of more than 30 s [25,53]. This threshold is a strong indicator of risky behaviour in our dataset, a result consistent with Van Houten et al.'s [54] and Ren et al.'s [55] behaviour findings showing that shorter pedestrian wait-times lead to better compliance. Moreover, the city where the average waiting time was significantly higher (Quebec: 45 s compared to 33 s in Montreal) is also the one with much higher odds of risky behaviours for all outcomes. This is not surprising since these two cities practice different approaches to how pedestrians are integrated into traffic phases. As a result, it seems that many pedestrians in Quebec City know that they will likely need to wait a long time and thus reduce this significant wait time by crossing on red, possibly after looking for gaps in traffic. Thus, although such pedestrian phases are preferred by people with visual impairments [56,57] forcing pedestrians to wait a long time is making them pay for the danger that cars are creating and is leading to behaviour that endangers many of them.

Previous research linking higher volumes of traffic to more pedestrian compliance at traffic signals [58–61] is in line with our results though the number of lanes was found to be a strong predictor than the traffic volume (both highly correlated). The exception was for the Spring observations where COVID-19 traffic disruption might have changed usual crossing patterns at the observed intersections. In fact, the significant relationship between this season and greater propensity to start, finish and cross completely on red might be another demonstration of the influence of low traffic on risky behaviours (though we are not saying that increasing traffic would improve safety, only that it is linked to fewer pedestrian violations, likely due to the danger imposed).

Finally, in contrast to many previous studies that included distracted behaviour, we considered the potential impact of season on dangerous crossing behaviour. The spring seasons was associated with an increase in many of those behaviours, but caution should be taken as this was during the Covid-19 pandemic and traffic conditions (and living conditions) were significantly altered.

4.2. Distracted pedestrians

Our observations found that headphones were the most common distraction at roughly 16 %, followed by being with someone (roughly 15 %), then holding a cellphone (but not necessarily using it; roughly 12 %), and talking on a cellphone (roughly 2–3 %). In Yadav and Velaga's review [16] a wide variety of proportions of pedestrians using cellphones was reported from roughly 3 % to 59 %. Likely the context of such studies can play a role (less wealthy countries, student environments, etc.). Our study had a large variety of the general population was a across different built environments, which was rare in most previous studies. Studies that had a similar (or larger) number of intersections across different built environments reported ranges of 5.8 % [62], 13.6 % [35] and 18.5 % [63]. An important point to make is that in our observations, 12–13 % of people were holding a cellphone, but not looking at it while crossing.

As discussed above, the intersection design was a critical factor with respect to the likelihood of risky behaviour (or outcomes) such as finishing on red. Using a cellphone was associated with a decrease in such behaviour. In a study on how practitioners thought about distracted pedestrians, a third of respondents without much evidence believed that it was a responsible for 40 % of pedestrian deaths [64]. This highlights the need for studies that focus on behaviour that causes danger, not simply something that victims of traffic violence do that makes them walk slower [16,33] which is also found for people who are walking with a companion [38], elderly, and children. As argued [64], consistent with Vision Zero, the focus should be more on who did the hitting that causes death.

Our observations found that holding a cellphone was associated with a decrease in risky behaviour. This might be explained in two ways: 1) individuals are aware that they are not fully paying attention, and so rely on the traffic signals more; 2) the cellphone makes waiting longer more bearable, thus not crossing despite longer waiting times. Previous studies reported associations between cellphone use and unsafe behaviours such as: walking slowly, not checking traffic before crossing or during crossing (women only) [34,36,37]. However, the contexts of those studies were the suburbs, a university campus, and downtown Seattle. None of them considered the crossing context when analyzing those behaviours. As well, those studies were conducted some years ago and people may have adjusted their behaviours while crossing as a result of warmings. One other study found that mobile phone distraction significantly impairs reaction time to green signal [65]. This later starting might be a technique of waiting for others to start and assuming that it is then safe. The unsafe behaviour is sometimes contrasting with some research reporting walking faster (with headphones) and others walking slower (while talking – with or without a cellphone). Our results put into perspective the "victim blaming" we see in road safety prevention on this specific topic [66,67].

4.3. Strengths and limitations of the study

This study had limitations related to gathering data through observations. For example, an objective measure of the speed of crossing the street was not captured which was previously found to be influenced by distractions. There is conflicting evidence on whether distraction affects how often pedestrians look both ways. It has been suggested distracted pedestrians search (i.e., turning head to check for traffic) less, however very few people even those who are not distracted looked both ways. Furthermore, our observations did not account for approaching vehicles, which could significantly impact pedestrian behaviour. Therefore, it is recommended that future studies incorporate considerations of approaching cars when observing pedestrian behaviour. In this study only, head movement was considered (whether they looked one or two ways). Future studies should take into account this while observing pedestrian behaviour. Due to mask wearing during the pandemic (1 of the 3 data collection period), some distractions such as small Bluetooth earbuds may have been missed. Also, it is not possible to know the exact age of people, and some misclassification likely occurred. Not all pedestrians can be observed at the same time with this protocol, and how the random selection relates to all pedestrians is unknown. However, this method follows most previous studies on the subject. Observations were also limited to a 3-h daytime period and some groups of the population may not normally travel at those times. Furthermore, our study was conducted in urban settings in Canada, and the findings may not be generalizable to pedestrian behaviours in rural areas or in different countries with distinct urban infrastructure and cultural norms. Another limitation is the potential influence of observer bias on data collection though consistency between observers was teste. Lastly, despite efforts to minimize bias through standardized observation protocols, subjective interpretations of pedestrian behaviours may have introduced inaccuracies.

On the other hand, the strength of this study lies in the large number of observed pedestrians in a variety of settings. Accordingly, all of our findings highlight the need to perform naturalistic observational studies in order to fully comprehend the role of individual and environmental variables on dangerous crossing behaviours. Our results suggest that intersection design and traffic signal operation, especially waiting time, is more crucial than distractions or other pedestrian's individual characteristics with respect to risky crossing behaviour. The time given to cross also seems to be a problem as older pedestrians are much more likely to finish on red having started on green. Our results support the new paradigm of Vision Zero which puts increased emphasis on the role of design in improving safety for all road users. To strengthen statistical results, future studies could consider hierarchical/mixed logistic regression model as the method of analysis, based on our observed data structures.

4.4. Implications for policy and practice

The findings of this study have several implications for policy and practice aimed at improving pedestrian safety. Firstly, our results suggest that traffic signal programming can have a significant impact on pedestrian behaviour. Therefore, traffic engineers and urban planners should consider shorter wait times at traffic signals for pedestrians to reduce the likelihood of risky behaviour such as non-compliance with traffic signals. Secondly, the results indicate that distractions such as cellphone use do not necessarily increase the likelihood of risky pedestrian behaviour. Rather, the distraction might help pedestrians to tolerate longer waiting times and encourage them to wait for the signal before crossing. Therefore, prevention programs and policies should not focus on blaming pedestrians for their distractions, but rather work to improve the design of the built environment and the traffic signal programming to enhance pedestrian safety. Thirdly, the study highlights the importance of pedestrian infrastructure and its impact on pedestrian safety. For instance, the presence of central islands in larger intersections was found to be associated with significantly riskier behaviours here. However, such components can be very important for individuals who cannot walk quickly. Finally, this study underscores the need to provide more time for crossing as it was demonstrated that elderly people who started on green were much more likely to finish on red potentially endangering them. Overall, this study demonstrates the need to focus on creating safe systems that promote or result in safer outcomes.

5. Conclusion

This study examined pedestrian crossing behaviour through direct observation at intersections in two Canadian cities. We examined the variables related to risky crossing behaviour such as starting, ending, and completely crossing on red at intersections. The findings demonstrate the importance of geometric design and traffic signal programming, taking all age groups and gender into consideration. A key design factor to reduce the likelihood of risky crossings was having short wait times (under 30 s). Other factors such as more traffic lanes likely reduce risky behaviours because of the danger imposed. Individuals doing behaviours often proposed as safe behaviour such as looking at traffic were highly associated with doing risky crossings as the individuals were likely checking for gaps in traffic. A critical problem identified for these cities was that elderly were much more likely to finish on red despite having started on green suggesting that the crossing times given for pedestrians are not inclusive. Distractions were not found to increase risky behaviours in all cases, and were found to reduce the likelihood of starting on red and crossing completely on red. Individuals with headphones were less likely to finish on red having started on green. From a perspective of designing safe systems, research should continue to examine the effectiveness of interventions that address the design (under the control of traffic engineers) in promoting pedestrian safety in diverse urban settings.

CRediT authorship contribution statement

Mohsen Miladi: Writing – original draft, Methodology, Conceptualization. **E. Owen D. Waygood:** Writing – review & editing, Supervision, Formal analysis, Data curation, Conceptualization. **Marie-Soleil Cloutier:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Bobin Wang:** Supervision, Formal analysis. **Zeinab Ali Yas:** Writing – review & editing, Validation, Formal analysis.

Declaration of competing interest

The Authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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