Analyzing the effect of micro-scale walkability on walking behavior

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A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Master of Science in Geography

March 2023

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ABSTRACT

Walkability, which is a conceptualization of the factors of the built and social environment that influence walking behaviour, can be understood at different scales and level of objectivity. Subjective walkability, a measure of the perceived friendliness of walking in an area, has been less commonly assessed than objective measurements, even though it has been shown that the latter are limited in their ability to capture the experience of walking in diverse settings. Similarly, limited research has analyzed on the relationship between the built-environment and walking behaviour varies between social groups. Walkability metrics have also been more commonly used at the meso-scale than the micro-scale even though the latter have been shown to be more closely linked to the walking experience and equity issues. This MSc Thesis aims to evaluate the applicability of a micro-scale walkability index (MAPS-Mini Audit tool) compared to a commonly used meso-scale index (Walkscore©) to (1) understand the predictors of subjective walkability and (2) to understand how these measures interact with socio-demographic characteristic when modelling walking behavior. In the first part of this research, I study how built-environment and land-use predictors of subjective walkability vary between travel and leisure walking. To do so, data was collected from 848 street segments in Montreal, Canada using the MAPS-mini audit tool, external measurements including Walkscore© as well as synthetic subjective walkability scores. Mixed effect multilevel models were generated by using travel and leisure subjective walkability scores as dependent variables and built environment features as independent variables. In the second part of this research, I analyze the interaction between walkability indices (MAPS-Mini audit tool and Walkscore©) and socio-demographic characteristic when modelling walking behavior using trip data from Montréal, Canada. Logistic regressions are used to model the probability of adults walking to destinations as a function of trip, person, and household characteristics, as well as walkability indices for the household location. Sensitivity analyses are conducted for four socio-demographic variables – gender, age, household income, and presence of children below 13 years old in the household – based on interactions with each of the walkability indices. For Chapter 1, results show that statistically significant positive micro-scale predictors of perceived walkability differed between walking for travel and walking for leisure. Walkscore© was found to have a weak but significant effect on perceived

walkability for travel, but no effect for leisure. In Chapter 2, interactions for all variables for both indices aside from Walkscore©'s interaction with gender are significant. Differential interactions are observed between the two indices for household income and presence of children. Overall, findings highlight the need to move towards a multi-scalar approach to walkability, by using data at the street and neighborhood level. Objective and subjective walkability measures should be used as complementary of each other, and socio-demographic characteristics of pedestrians should be considered as moderating factors of the effect of the built environment on walking behavior.

RÉSUMÉ

La marchabilité, qui est une conceptualisation des facteurs de l'environnement bâti et social influençant la marche, peut être analyser à différentes échelles et niveaux d'objectivité. La marchabilité subjective, une mesure de la perception de convivialité de l'environnement piéton, a été moins étudiée que les indices de marchabilité objectifs et ce, même s'il a été démontré que ces derniers sont limités dans leur capacité à refléter l'expérience piétonne dans des environnements variés. De plus, peu de recherche à analyser comment la relation entre l'environnement bâti et les habitudes de marche varie entre diverse groups sociaux. La marchabilité a été mesurée plus fréquemment à l'échelle locale qu'à l'échelle de la rue même si cette dernière approche a été associée davantage à l'expérience de marche et à l'équité entre les groupes sociaux. Ce m/moire de maitrise vise à évaluer l'applicabilité d'une mesure de la marchabilité à l'échelle de la rue (outil MAPS-Mini) comparément à celle d'une mesure à l'échelle locale (Walkscore©) pour (1) évaluer les facteurs influençant la marchabilité subjective et pour (2) analyser comment ces mesures interagissent avec les caractéristiques socio-démographiques lorsqu'on modélise les habitudes de marche. Pour ce faire, des données ont été récoltées pour 2497 segments de rues à Montréal en utilisant l'outil MAP-Mini, des données externes comme le Walkscore© et des scores synthétiques de marchabilité subjective. Dans la première partie de cette recherche, j'étudie comment les caractéristiques de l'environnement bâti contribuant aux perceptions de marchabilité varient entre la marche utilitaire et la marche de loisir. Des modèles multiniveaux sont générés en utilisant les scores de marchabilité subjective pour la marche utilitaire et la marche de loisir comme variable dépendantes et les éléments de l'environnement bâti comme variables indépendantes. Dans la deuxième partie de cette recherche, j'analyse les interactions entre des indices de marchabilité (l'outil MAPS-Mini et Walkscore©) et les caractéristiques socio-démographiques des piétons durant la modélisation des habitudes de marche à l'aide de donnée de déplacement pour Montréal. Des régressions logistiques sont utilisées pour modéliser la probabilité qu'un adulte marche à une destinations en fonction de caractéristiques du déplacement, de la personne, du ménage et des indices de marchabilité pour l'emplacement du ménage. Des analyses de sensibilité sont réalisées pour quatre variables socio-démographiques – le genre, l'âge, le revenu par ménage et la présence d'enfant de moins de 13 ans dans le ménage – en se basant sur les interactions entre chacune et les indices de marchabilité. Pour le premier chapitre, les résultats démontrent que les facteurs de l'environnement bâti à l'échelle de la rue qui ont un effet statistique positif sur la marchabilité subjective diffèrent entre la marche utilitaire et la marche de loisir. Il est aussi observé que le Walkscore© a un effet faible mais significatif sur la marchabilité subjective pour le déplacement, mais aucun effet pour la marche de loisir. Dans le deuxième chapitre, les interactions entre chaque variable et les indices de marchabilité sont significatifs à l'exception de l'interaction entre le Walkscore© et le genre. Des interactions différentes sont observées entre les deux indices pour les variables de revenu par ménage et de présence d'enfants dans le ménage. Globalement, les résultats de cette étude démontrent le besoin de transitionner vers une approche multiscalaire à la marchabilité en combinant des indices à l'échelle de la rue et à l'échelle locale. Les indices de marchabilités objectifs et subjectifs devraient être utilisé de façon complémentaire et les caractéristiques socio-démographiques des piétons devraient être considérées comme facteurs de modération lors de l'étude des effets de l'environnement bâti sur les habitudes de marche.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my supervisor Prof. Kevin Manaugh whose guidance throughout my Master's was crucial to my academic learning experience.

I would also like to thank my two committee members, Profs. Ahmed El-Geneidy and Mylene Riva for their feedback at several steps of my Master's research.

Special thanks goes out to Julia Daley with whom I collected the data that I used for my first chapter and to Prof. Léa Ravensbergen, assistant professor at McMaster University for helping us in that process. I would also like to thank Gregory Butler (Public Health Agency of Canada) for providing the idea that sparked this research and Rania Wasfi (Public Health Agency of Canada) for providing feedback and guidance on the analysis of statistical models.

I would like to give special thanks to the Social Sciences and Humanities Research Council of Canada (SSHRC) for partially funding the research carried out in this thesis as well as McGill University's Faculty of Science for granting me with the Grad Excellence Award and the Alexandra Cowie-Irwrin Fellowship which helped with my expenses during this Master's degree.

CONTRIBUTION OF AUTHORS

Chapters 2 and 3 of this thesis are manuscripts that have been published or have been submitted for publication and for which I am the primary author. Chapter 2 is based on the manuscript titled *Factors influencing subjective walkability: results from built environment audit data* which was published in the Journal of Land Use and Transport in 2022 for which the co-authors are Julia Daley, Prof. Léa Ravensbergen, my supervisor Prof. Kevin Manaugh, Rania Wasfi (Public Health Agency of Canada), Gregory Butler (Public Health Agency of Canada) and Prof. Ahmed El-Geneidy. The authors contribution to the paper were as follows: Study conception and design: Rodrigue, Manaugh, El-Geneidy; Data collection: Rodrigue, Daley, Ravensbergen, Butler & El-Geneidy; Analysis and interpretation of results: Rodrigue, Manaugh, Wasfi & El-Geneidy.

Chapter 3 is based on the manuscripts titled *Analyzing interactions of individuals' socio-demographics with walkability when modelling walking behavior* submitted to the Journal of Transport Geography in 2022 which was co-authored with Prof. Kevin Manaugh and Prof. Ahmed El-Geneidy. The authors contribution to the paper were as follows: Study conception and design: Rodrigue, Manaugh, El-Geneidy; Data collection: Rodrigue, Manaugh & El-Geneidy; Analysis and interpretation of results: Rodrigue, Manaugh & El-Geneidy.

For both studies, I carried out the data collection, data cleaning, analysis, and writing, as well as preparation of the article for submission. Profs. Manaugh and El-Geneidy provided guidance and feedback on the methodology employed in both studies as well as revisions of the manuscripts. I have prepared all sections of this document under the direction of my supervisors.

LIST OF TABLES AND FIGURES

CHAPTER 1 – INTRODUCTION

Over the past two decades, researchers in a wide range of fields have reported clear evidence for the health and environmental benefits of increased levels of walking (Andrews et al. 2012, Lee and Buchner 2008, Tobin et al. 2022). Recent work by multiple transport, planning and public health researcher framed walkability as being the subcomponent of Active Living Environments (ALEs) reflecting the factors of built end social environment that promote walking behaviour (Tobin et al., 2022), which is the definition that will be used in this MSc Thesis. That being said, there have been ongoing debates about how to properly define and conceptualize "walkability" (Andrews et al. 2012, Tobin et al. 2022, Shashank and Schuurman 2019, Forsyth 2015). First, walkability can be measured at different scales, mainly the micro-scale (i.e. street or intersection level) or meso-scale (i.e. small area level) (Bivina, Gupta, and Parida 2020). While micro-scale walkability often entails detailed street audit processes, meso-scale walkability indices – which are at the neighborhood or small area-level – are usually generalizable, composite measures such as intersection and population density (Arellana et al. 2020, Fonseca et al. 2021). In addition to differences in spatial scale, scholars and practitioners working in the field of walkability can often be characterized as having one of two preoccupations: 1) promoting increases in walking trips conducted or 2) improving the walking experience (i.e., the pleasantness of the walk, feeling of comfort or security). These objectives, while not mutually exclusive, can lead to drastically different policy outcomes. For example, focusing on improving walking rates might target areas were walking is less prevalent, which are more likely to be wealthier suburban areas as these areas tend to have higher car ownership rates. On the opposite, focusing on improving walking experience is more likely to lead to interventions where there are high levels of walking but unsafe and unpleasant pedestrian environments which are more likely to be disadvantaged areas as lower-income individuals tend to have less access to alternative modes of transportation (Manaugh and El-Geneidy 2011). These different objectives also relate to another frequent division of factors influencing walking behavior: trip purpose. Indeed, past research has emphasized differential predictors of walking behavior for travel walking (i.e., walking to a set destination) and leisure walking (i.e., walking without a fix destination, leisure walking) (Hsieh and Chuang 2021). Lastly, the relationship between the built environment and walkability can also be understood objectively – as a direct impact of the built and social environment on walking behaviour – and subjectively – as an indirect link moderated by one's socio-demographic characteristics and preferences (Liao et al. 2020, Manaugh and El-Geneidy 2011, De Vos et al. 2022). These different components of the link between the built environment and walking behaviour are represented in Figure 1.

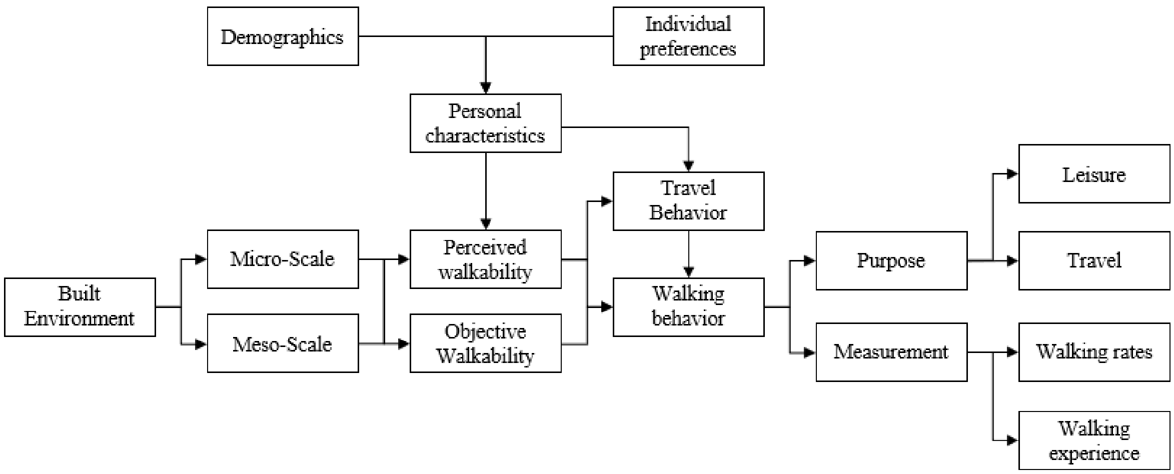


Figure 1 Conceptual representation of the links between the built environment and walking behavior

With all these different conceptualisation of walkability, a variety of methods have been developed to measure it. Nevertheless, the majority of the walkability research remains centered on objective, meso-scale measures generally used when aiming to promote increased frequency of walking for travel (Fonseca et al. 2021). While these measures have been associated with impacts on walkability, they have also been shown to be limited in their ability to accurately predict walking rates (Consoli et al. 2020, Hajna et al. 2013, Herbolsheimer et al. 2020, Herrmann et al. 2017, Shashank and Schuurman 2019, Tuckel and Milczarski 2015) and even more so to capture the subjective experience of walking in diverse settings (Battista and Manaugh 2017, Gebel, Bauman, and Owen 2009, Koohsari et al. 2021, Tuckel and Milczarski 2015, Yang and Diez-Roux 2017). Past research has also shown that general, area-based interventions, aimed at increasing walking rates without social contextualization can widen existing social inequities (Hall and Ram 2018, Manaugh and El-Geneidy 2011, Shashank and Schuurman 2019)

Subjective preferences behind walking behaviours have been shown to be important mechanisms through which the built environment impacts individuals' walking behaviors (Arvidsson et al. 2012, Consoli et al. 2020, Herbolsheimer et al. 2020, Jun and Hur 2015, Manaugh and El-Geneidy 2013, Nyunt et al. 2015). However, such considerations have remained limited in the literature (Bohte, Maat, and Van Wee 2009, Fonseca et al. 2021). Similarly, while past research has shown that walking behaviours vary with gender (Hidayati, Tan, & Yamu, 2020), age (Stafford & Baldwin, 2018), income (Manaugh & El-Geneidy, 2011) and other socio-demographic and socio-economic factors, considerations of socio-demographic characteristics as crucial moderating factors of the relationship between the walking environment and walking behavior have been scarce with these variables being often modelled as control variable. Pathways to better account for these understudied issues have been highlighted using micro-scale walkability elements, although such studies have occupied a small place in walkability research (Fonseca et al. 2021). Indeed, characteristics of the pedestrian environment have been shown to influence avoidance or approach behaviors (Ortiz-Ramirez, Vallejo-Borda, and Rodriguez-Valencia 2021) and to help reduce observed differences in walking behaviour between social groups (Clifton and Livi 2005, Jensen et al. 2017, Lee and Dean 2018).

Given these previous limitations in the literature, a growing body of research has emphasized the need to reintegrate pedestrians in the understanding of the relationship between the built and social environment and walking behavior (Consoli et al. 2020, Jun and Hur 2015, De Vos et al. 2022). This include quantifying walkability along different levels of objectivity and scale to provide a richer understanding of what explains walking experience (Herbolsheimer et al. 2020, Manaugh and El-Geneidy 2013) and to help reframe walking behaviour as not solely dependent on whether someone walks for a trip, but whether they *want* to. It also entails assessing how the built-environment interacts with socio-demographic characteristics to influence walking behavior and how specific walkability indices might hinder or promote increased equity between social groups.

This MSc Thesis aims to assess how micro-scale walkability contributes to (1) perceived walkability (Chapter 2) and (2) variations in probability of walking between socio-demographic groups (Chapter 3) while also contrasting it to commonly used meso-scale indices. To do so, micro-scale built-environment data was collected through a street audit tool (MAPS-Mini audit tool) in two waves in Summer 2021 (Chapter 2) and Summer 2022 (Chapter 3). The data used in this Master's Thesis was collected as part of a longitudinal, quasi-experimental research project by the Transportation Research at McGill (TRAM) group on the short and long-term impacts of a new light-rail system – the Réseau Express Métropolitain – in Montréal, Canada. As such, micro-scale audit data was collected in a 500-meter area (Summer 2021; Wave 1) and 1000-meter area (Summer 2022; Wave 2) surrounding the new light-rail stations. Other data collected in this research project which were not used in this MSc Thesis, includes multi cross-sectional and longitudinal surveys of travel behaviour, attitude towards transport, residential history and health outcomes.

To assess how micro-scale walkability contributes to perceived walkability (Chapter 2), I employ mixed effect multilevel models to predict synthetic subjective walkability scores for travel and leisure walking from micro-scale and meso-scale built environment features. Then, to evaluate how the effect of micro-scale and meso-scale walkability on frequency of walking changes between socio-demographic group (Chapter 3), I employ logistic regression modelling the probability of taking a trip by walking from trip, person, household and built-environment characteristics – assessed through one micro-scale and one meso-scale walkability index. I then interact four socio-demographic variables with the micro-scale and meso-scale indices separately and use the result of the interactions to conduct sensitivity analysis by varying the values of the socio-demographic variables.

Relevant background literature is discussed in each of the core chapters (Chapter 2 & Chapter 3). This research is expected to contribute to the literature by combining and contrasting walkability measures across different scale as well as through the assessment of walking behaviour as both perceived walkability (i.e. walking experience) and frequency of walking. Through both chapters, I aim to emphasize the need to shift away from walkability as centered primarily on promoting frequency of walking for travel towards walkability as a multi-scalar, inherently subjective concept that is intrinsically dependent on individuals' perceptions and socio-demographic characteristics as well as the purpose of their trips. Given the new light-rail around which data was collected is set to open in phases between 2023 and 2027, changes in the built environment audited are expected. As such, it will be possible to build upon the research conducted in this MSc Thesis later as the light-rail' timeline progresses to analyze changes in walking behavior as a result of changes in the built-environment.

CHAPTER 2 – FACTORS INFLUENCING SUBJECTIVE WALKABILITY: RESULTS FROM BUILT ENVIRONMENT AUDIT DATA

Abstract: Subjective walkability is a measure of the perceived friendliness of walking in an area. Though subjective walkability is less commonly assessed than objective measurements, the latter often fail to reflect the experience of walking. This study aims to better understand subjective walkability and how it varies between travel and leisure walking by investigating its relationship with the built environment and land use characteristics. Data was collected from 848 street segments in Montreal, Canada using the MAPS-mini audit tool, external measurements including Walkscore© as well as synthetic subjective walkability scores. Mixed effect multilevel models were generated by using travel and leisure subjective walkability scores as dependent variables and built environment features as independent variables. Statistically significant positive predictors of perceived walkability differed between walking for travel and walking for leisure. Walkscore© was found to have a weak but significant effect on perceived walkability for travel, but no effect at all for leisure. A multi-scalar approach both at the street and neighborhood level making use of a combination of objective and subjective walkability measures should be employed to study predictors of walking behavior. Lastly, distinctions of walking behaviors based on trip purpose should be integrated in future research.

Keywords: Walkability, Subjective Walkability, Audit, Built Environment

Highlights

- Multilevel mixed effects models were used to account for inter-rater variability
- Differences exists between subjective walkability for travel and for leisure
- Subjective walkability differs greatly from objective walkability
- Walkability scores that consider objective and subjective measures is needed
- Walkability measurements at the micro and meso-scale should be used jointly.

2.1. INTRODUCTION

2.1.1 Conceptual Framing

The health and environmental benefits of increased levels of walking are clear and have received increased attention in many fields over the past two decades (Andrews et al. 2012, Lee and Buchner 2008, Tobin et al. 2022). While a large body of literature has been dedicated to studying the determinants of walking behaviours, debates remain about how to properly define and conceptualise “walkability” (Andrews et al. 2012, Tobin et al. 2022). Indeed, walkability definitions and frameworks vary widely between researchers. This will often impact the elements of the built and social environments which are considered and the measures used to assess them (Shashank and Schuurman 2019). On a broader scale, walkability can be conceptualized as a sub-component of Active Living Environments (ALEs) which focuses specifically on the impact of the built and social environment on walking behaviors (Tobin et al. 2022). Walking behaviors can be separated into either walking for travel, also referred to as utilitarian or purposive walking which represent walking to a fix destination (i.e. commuting, running errands or going to any pre-determined location by walking), and walking for leisure, also referred to as recreational or discursive walking, which represent walking without going to a set destination (Hsieh and Chuang 2021). Such conceptual distinctions are important as previous research has established that determinants of both travel and leisure walking vary with land-use diversity being relevant for walking for travel while aesthetics and walking facilities being more relevant for leisure walking (Boarnet et al. 2011, Inoue et al. 2010, Inoue et al. 2011). For the sake of consistency, we will be using walking for travel and walking for leisure to refer to the two types of walking behaviors for the rest of this paper.

Like walking behaviours, the concept of walkability can also be divided into two components: meso-scale walkability which primarily – but not exclusively – centers around the ease of reaching destinations and micro-scale walkability which focuses predominantly on the built and social environment features that pedestrians directly interact with while walking. Walkability can also be aggregated at the macro-scale for a neighborhood or city level from micro or meso-scale features. One of the foundational framework used in walkability research, the 3 Ds (diversity of land use, residential density, and design of the streets connectivity) developed by Cervero & Kockelman in 1997 (Cervero and Kockelman

1997), primarily focuses on macro-scale features of walkability. Expansions of this framework integrated destination accessibility, distance to transit (Ewing and Cervero 2001, Ewing et al. 2009) as well as demand management and demographics (Ewing and Cervero 2010) which allowed for a more complex understanding of walking behaviours. The integration of demographics, while not a characteristic of the walking environment, points out to an integration of notions of equity and differential interactions with the built environment based on individual characteristics (e.g. age, gender, income). This latter point is important as it allows for a distinction between objective walkability measurements – which assess the built and social environment independently of the identity and perceptions of pedestrians – and subjective walkability measurements – which integrates the intermediate factor of pedestrians' perceptions of the built and social environment to understand walking behaviours. Subjective preferences behind walking behaviours have been shown to be important mechanisms through which the built environment impacts individuals' walking behaviors (Arvidsson et al. 2012, Consoli et al. 2020, De Vos et al. 2022, Herbolsheimer et al. 2020, Jun and Hur 2015, Manaugh and El-Geneidy 2013, Nyunt et al. 2015). Past research has highlighted that characteristics of the walking environment can influence avoidance or approach behaviors through the primary emotional and psychological reactions of pedestrians which are inherently dependant on individual preferences and characteristics (Ortiz-Ramirez, Vallejo-Borda, and Rodriguez-Valencia 2021).

Lastly, a conceptual distinction must also be made on what measurement of walking behavior should be considered to establish the priority of a geographical area to receive interventions to improve walkability. Indeed, when aiming to provide walkability improvements, one can either focus on improving walking rates or walking experience. Improving walking rates means that areas of focus will be the ones where walking is less prevalent which are likely going to be wealthier suburban areas (Manaugh and El-Geneidy 2011). On the opposite, focusing on improving walking experience will shift the focus on areas with significant existing levels of walking but poor perceived walkability by pedestrians (i.e. captive pedestrians) which are more likely to be areas with lower incomes (Manaugh and El-Geneidy 2011).

2.1.2 Methods in walkability research

The latest systematic review of the methods used in the field of walkability separates the built environment factors considered into six categories: land-use, accessibility, street connectivity, pedestrian facility and comfort, safety and security, as well as streetscape design (Fonseca et al. 2021). The first three categories – land use, accessibility and street connectivity – have been mostly used at the meso-scale while the latter three – pedestrian facility and comfort, safety and security as well as streetscape design – have been mainly used to evaluate walkability at the micro-scale. While these categories are universally applicable, their relative importance will vary through time and space (Berry et al. 2017) as well as from one researcher to another (Shashank and Schuurman 2019). That being said, there are still predominant measurements used in the field of walkability research which are for the most part both objective as well as meso-scale (Fonseca et al. 2021, Hajna et al. 2015). These include residential, population, amenities, and intersection densities as well as Retail Floor Area (RFA), entropy measures quantifying land use diversity at a meso-scale and distance to amenities (Fonseca et al. 2021). These measures have been used in combination with one another to form composite indices such as Walkscore©, a popular proprietary tool designed for real-estate which integrate distance to amenities with intersection density to quantify access to opportunities in an area on a scale of 0 to 100 (Carr, Dunsiger, and Marcus 2010). Another similar composite walkability index is Frank's walkability index which integrates intersection and residential density along with entropy measures of land use mix and RFA (Frank et al. 2010). While these built environment measures have been demonstrated to have an impact on walkability, they have also been shown to be limited in their ability to accurately predict walking rates (Consoli et al. 2020, Hajna et al. 2013, Herbolsheimer et al. 2020, Herrmann et al. 2017, Nyunt et al. 2015, Shashank and Schuurman 2019, Tuckel and Milczarski 2015) and even more so to capture the subjective experience of walking in diverse settings (Battista and Manaugh 2017, Gebel, Bauman, and Owen 2009, Koohsari et al. 2021, Tuckel and Milczarski 2015, Yang and Diez-Roux 2017). This latter reality is particularly true when looking separately at travel and leisure walkability – a distinction that is rarely made when using such walkability measurement (Wasfi, Steinmetz-Wood, and Kestens 2017). These issues can be partly attributed to the lack of consideration of micro-scale characteristics such as sidewalk presence or maintenance as well as tree cover (Herrmann et al. 2017).

To address such shortcomings, a smaller portion of the walkability scholarship has simultaneously been dedicated to built environment factors mostly assessed at the micro-scale (i.e. pedestrian facility and comfort, safety and security as well as streetscape design) and which have been mainly used to evaluate walking experience (Fonseca et al. 2021). One of the most common tools used to assess these factors objectively have been audits, which are observational surveys of the built and social environment. Audits, through their focus on micro-scale features, have the advantage of providing more detailed portraits of the built environment which can be better used to predict walking experience at the street level. Amongst the most popular audit tools used are the Irvine Minnesota Inventory (Day et al. 2006) and the MAPS audit tool (Cain et al. 2015, Sallis et al. 2015). While such tools present a more accurate portrait of the built environment, they remain limited in their ability to predict actual walking rates, particularly for leisure walking (Boarnet et al. 2011, Sallis et al. 2015). Nevertheless, the added level of detail they provide as well as their focus on micro-scale environments makes them more suitable to the evaluation of the effect of the built environment on walking experiences than the previously discussed measures used to assess the ease of reaching destinations (Blecic et al. 2016, Brown and Jensen 2020).

Lastly, in contrast to the larger body of research that has made use of objective measurements of the built environment, subjective walkability has been less often integrated in past studies assessing the relationship between built environment features and walking behaviors (De Vos et al. 2022, Fonseca et al. 2021). Indeed, while subjective preferences behind walking behaviours have been proven to be important mechanisms through which the built environment impacts individuals (Arvidsson et al. 2012, Consoli et al. 2020, Herbolsheimer et al. 2020, Jun and Hur 2015, Manaugh and El-Geneidy 2013, Nyunt et al. 2015), their consideration remains limited in research analyzing the impact of the built environment on walkability (Bohte, Maat, and Van Wee 2009, Fonseca et al. 2021). The current scholarship can be divided along two factors, whether it is qualitive or quantitative as well as the spatial scale of the unit of analysis. With the quantitative research done on subjective walkability, the most common approach has been to assess the perceived accessibility and ease of walking at a neighborhood level (Alidoust, Bosman, and Holden 2018, Bodeker 2018, Hanák, Marović, and Aigel 2015, Hanibuchi et al. 2015) with tools such as the Neighborhood Environment Walkability Scale (NEWS) (Brown and Jensen 2020, Jensen et al. 2017, Notthoff and Carstensen 2017). A limited body of literature has made use of quantitative methods to quantify the perceived pedestrian friendliness at the micro-scale level (Arellana et al. 2020, Fonseca et al. 2021) with synthetic subjective walkability scores and machine learning evaluation built upon such synthetic scores being the primary tools used (Blecic, Cecchini, and Trunfio 2018, Blecic et al. 2019, Yameqani and Alesheikh 2019). On the qualitative side, research has been more spread out with past research making use of walking interviews (Alidoust, Bosman, and Holden 2018, Herrmann-Lunecke, Mora, and Vejares 2021) and mental mapping (Bodeker 2018) as well as conducting focus groups to build decision processes relying on subjective walkability measures to better inform urban policy (Fancello, Congiu, and Tsoukias 2020, Moura, Cambra, and Gonçalves 2017). Overall, potential predictors of perceived walkability can be categorized according to their level of objectivity (Battista and Manaugh 2018, Blecic et al. 2016) with the presence of sidewalks being on the objective end, cleanliness or pollution in the middle and psychological effects of the environment on the subjective end. Significant street-level predictors found in previous research include the presence of sidewalks, sidewalk width, streetlights, and shading (Blecic et al. 2016, Jensen et al. 2017). The impact of specific predictors on subjective walkability has also been shown to vary within populations according to socio-demographic conditions (Adkins et al. 2019, Manaugh and El-Geneidy 2011, Moura, Cambra, and Gonçalves 2017, Shashank and Schuurman 2019).

Building upon previous research, this paper aims to consider a combination of built-environment factors both at the meso-scale and micro-scale to predict the experience of walking on a street as quantified through synthetic subjective walkability scores. Our paper expands on past research by differentiating between travel and leisure walking, integrating a larger sample, and accounting for raters' effect on subjective scores through mixed effects multilevel modelling in which raters are added as a second level. Highlighting the best predictors of subjective walkability and providing a realistic application of currently used methods to quantify walking experience allow us to highlight better leverage points for improving the experience of walking, which many practitioners are aiming for.

2.2. DATA AND METHODS

2.2.1 Built Environment Data

Data were collected as part of the first wave of a built environment audit conducted around the future stations of the upcoming Reseau Express Metropolitan (REM), a new light-rail train (LRT) system in Montreal, Canada (Daley et al. 2022). Areas sampled, which were within a 500-meter service area of new stations of the REM are displayed in Figure 2. In total, 848 street segments were audited using an adapted version of the MAPS-mini audit tool (Daley et al. 2022), which has been validated in previous research (Sallis et al. 2015). Data collection took place on weekdays between 9:00PM and 5:00PM and required a total of 240 hours from 14 auditors which were all trained prior to the audit on the collection of the objective data. Auxiliary data such as Walkscore©, speed limits, and population densities were also integrated in the data set used (Daley et al. 2022).

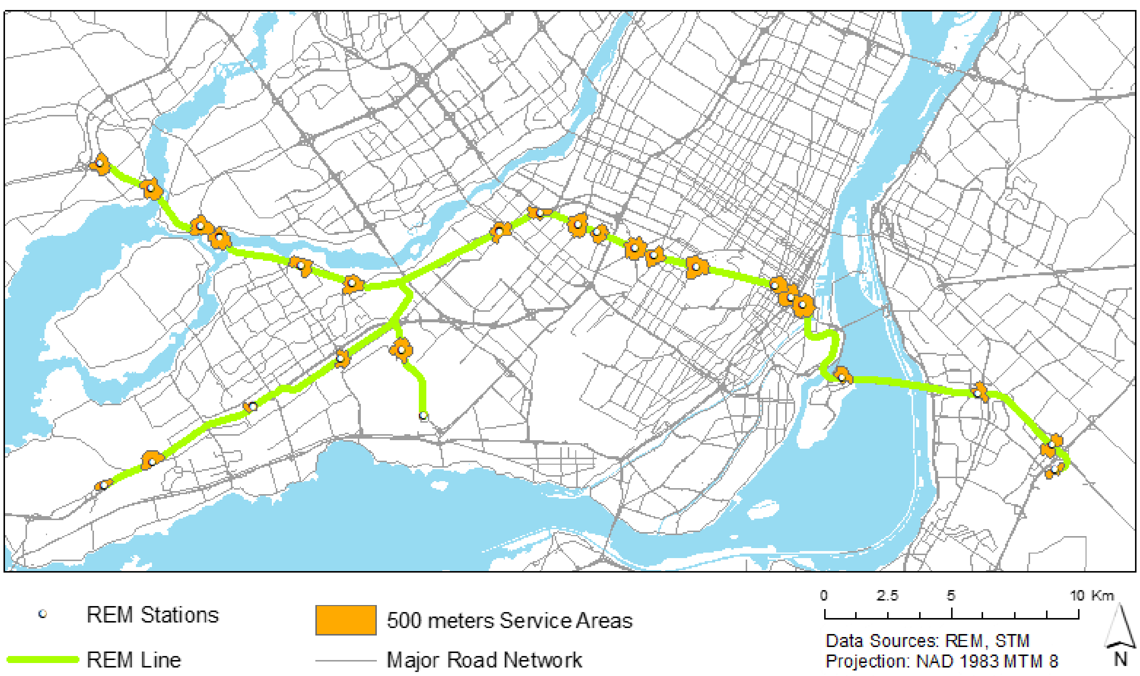


Figure 2 Service areas audited around the REM stations

2.2.2 Subjective Walkability Scores

As previously stated, the focus of this study is the walking experience component of walkability which framed the creation of the synthetic subjective walkability scores collected (described in Table 1). The distinction made between the two scores collected was explained to the raters as if they were to walk on the street segment to get to a particular destination (i.e. walking for travel) versus if they were to walk on it for a non-purposive walk (i.e. walking for leisure). Raters were given no additional directions on what to consider when scoring a segment to ensure that they would be scoring based on their own perception. All segments were scored in situ by raters.

Table 1 Synthetic subjective walkability scores

Question	Scale
On a scale of 1-10, how walkable would you rate this segment for travel?	1(completely unwalkable) – 10 (perfectly walkable)
On a scale of 1-10, how walkable would you rate this segment for leisure?	1(completely unwalkable) – 10 (perfectly walkable)

A first wave of data was collected in Summer 2021 at the same time as the built environment audit for all 848 segments by 12 of the 14 auditors. To control for the potential influence of the audit process on the subjective scoring, a second wave of subjective data was collected in Fall 2021 by 5 independent raters that had not been involved at any point in the audit process. In total, 314 segments were scored again during this second wave. The collected scores were used to replace the scores originating from the first wave for the given 314 segments thus maintaining only one subjective score entry per segment for each of the 848 segments for which built environment data had been collected.

Overall, all 17 raters were less than 40 years old; their average age was 25.4 years. 11 identified as men and six as women. Eight raters grew up in an urban setting, seven grew up in a suburban setting and the remaining two were from rural areas. Heterogeneity was also present in nationality between the raters. Conversely, there was homogeneity amongst raters in education levels as all had completed or were completing a university level degree. Lastly, it is important to note that all auditors were either working for McGill University's School of Urban planning or were students in the department of Geography with experience in walkability research. This decision was made based on resources available during the completion of the audit process. Implications from this decision on the results will be covered in the discussion section.

2.2.3 Multilevel regression models

Multilevel mixed effects models are used to estimate the factors associated with synthetic subjective walkability scores at the street level, the main exposure of interest (independent variables) are the physical and functional elements of the built environment identified through the audit or collected as auxiliary data. Audited segments are nested within raters (17 raters) to isolate the bias that could arise from the personal characteristics between raters and from the simultaneous collection of the built environment data (i.e., isolate the inter-rater variability in the subjective scores). Variability between raters' socio-demographic in term of gender, childhood environment and other socio-demographic are therefore captured together through the multilevel approach.

All built-environment components collected from the audit process (Daley et al. 2022) were used as independent variables in the model in addition to Walkscore© and other auxiliary data (e.g. speed limits, population density, median household income). Variation inflation factors (VIF) were calculated for both models with all independent variables with a factor above five being excluded from the model to avoid collinearity (Akinwande, Dikko, and Samson 2015). Concurrently, independent variables were individually tested for their significance in predicting the response variables (i.e. synthetic subjective walkability scores for travel and leisure) independently for both models. Non-significant variable that did not contribute to improve the prediction power of a given model were removed while those that did were kept as these acts as suppressor variables (i.e. they capture some level of variability that could otherwise be wrongly attributed to other variables) (Akinwande, Dikko, and Samson 2015). Both models were also tested separately for the influence of a rater having also acted as an auditor through the integration of a dummy variable for auditors. Table 2 displays descriptive statistics for fixed effects variables that were included in the final models. It should be noted that both dependent variables were normally distributed and have similar mean and standard deviation. Additionally, no significant differences were observed between men and women in mean subjective scores for utilitarian walking (5.95 and 6.47 respectively) or for walking for travel (5.75 and 5.69 respectively). To assess significance level of the models, the Bonferroni correction was applied meaning that the significance level was now the initial value (α = 0.05) divided by the number of variables included. For the travel model, this meant that the corrected significance level was 0.005 (10 variables) while it was 0.0045 (11 variables) for the model for leisure walking scores.

Table 2 Descriptive statistics of variables included in the statistic model

Variables	Mean	St. Dev	Min	Max
Dependent variables				
Subjective walkability score for travel	6.05	2.22	1	10
Subjective walkability score for leisure	5.73	2.3	1	10
Independent Variables				
Land-use				
Main Land use				
Residential	0.53	0.50	0	1
Vacant / Industrial	0.06	0.24	0	1
Commercial	0.22	0.42	0	1
Mixed	0.19	0.39	0	1
Parks (Count)	0.13	0.37	0	2
Parks (Binary)	0.88	0.33	0	1
Parking lots (Binary)	0.16	0.37	0	1
Transit Stops (Binary)	0.25	0.43	0	1
Accessibility				
Walkscore (normalized on 10)	6.18	2.73	0.4	9.9
Street Connectivity				
Cul-de-sac (Binary)	0.05	0.21	0	1
Safety and security				
Pedestrian light signal				
None	0.67	0.47	0	1
One intersection	0.20	0.40	0	1
Two intersections	0.13	0.34	0	1
Speed Limit [10km/h]	4.00	0.72	0	5
Streetlights				
None	0.07	0.25	0	1
Some	0.77	0.42	0	1
Ample	0.16	0.36	0	1
Pedestrian facility and comfort				
Benches (Binary)	0.25	0.43	0	1
Sidewalk buffer				
No	0.73	0.44	0	1
One side	0.10	0.29	0	1
Two side	0.17	0.38	0	1
Adequate Sidewalk maintenance (Binary)	0.64	0.48	0	1
Sidewalk tree cover				
0 - 25 % - no sidewalk	0.69	0.46	0	1
26 - 75%	0.26	0.44	0	1
76 - 100%	0.05	0.22	0	1
Streetscape design				
Adequate Building maintenance (Binary)	0.67	0.47	0	1

2.2.4 Walkscore correlation with subjective walkability

Simple regressions were conducted to explore the relationship between Walkscore© and the synthetic subjective walkability scores collected. In addition to that, specific segments were extracted to act as further examples to explain the results observed.

2.3. RESULTS

The statistical model predicting subjective walkability for travel yielded a conditional R^2 of 0.701 while the model predicting subjective leisure walkability obtained a conditional R^2 value of 0.578 (Table 3) suggesting a high and moderate explanatory power respectively compared to previous studies in the literature (Blecic et al., 2016). The lower conditional R^2 obtained for the leisure walking model suggests that while it predicts subjective scores for leisure walking rather well, there remain potential predictors that were not included in the data collected from the audit or from external sources. This is true for subjective walkability scores for travel as well, but to a lesser extent. A notable variance was also observed in the significance and magnitude of effect of some predictors between travel and leisure walking which is coherent with previous research (Tuckel & Milczarski, 2015).

The Intraclass correlation coefficient (ICC) measures the proportion of unexplained variance in the error term that is related to between class variation (i.e., between raters' variance (τ_{00})) from the total variance of the error term (i.e., the residual σ^2). The ICC suggests that 63% of the unexplained variance in the error term is related to between raters' variability in the walking for travel model. Similarly, for leisure walking subjective scores, 44% of the variance in the error term is explained through between raters' variability. The high ICC values confirm the importance of using a multi-level modeling approach. It also further highlights the variability of perceived walkability between individuals. Lastly, it should be noted that the integration of the auditor variable did not have any incidence on the models as it was neither significant nor did it change the significance or magnitude of the effect of other independent variables. The fact that all raters had knowledge of urban planning or walkability related literature could have also muted the potential bias from the audit process on their subjective walkability scores.

Table 3 Statistical Models Predicting Subjective Scores from micro-scale street characteristics

	Subjective Score for Travel			**Subjective Score for Leisure**		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	4.75	3.54 – 5.96	**<0.001**	6.48	5.33 – 7.55	**<0.001**
Land-Use						
Main land-use (Reference: Residential)						
Vacant / Industrial				-1.31	-1.88 – -0.74	**<0.001**
Commercial				-0.81	-1.20 – -0.43	**<0.001**
Mixed				-0.47	-0.84 – -0.10	**0.012**
Parks				0.83	0.47 – 1.19	**<0.001**
Parking lots				-0.65	-0.98 – -0.32	**<0.001**
Transit stops				-0.64	-0.95 – -0.32	**<0.001**
Accessibility						
Walkscore©	0.16	0.10 – 0.21	**<0.001**			
Street connectivity						
Cul-de-sac	-0.99	-1.47 – -0.50	**<0.001**			
Safety and security						
Pedestrian light signal (Reference: None)						
One Intersection	-0.37	-0.66 – -0.07	**0.014**			
Two Intersections	-0.01	-0.41 – 0.39	0.971			
Speed limit	-0.33	-0.49 – -0.18	**<0.001**	-0.56	-0.74 – -0.38	**<0.001**
Street lighting (Reference: None)						
Some	0.47	0.07 – 0.87	**0.020**	0.57	0.12 – 1.02	**0.014**
Ample	0.85	0.35 – 1.35	**0.001**	1.23	0.67 – 1.79	**<0.001**
Pedestrian facility and comfort						
Benches	0.47	0.22 – 0.73	**<0.001**	0.61	0.29 – 0.94	**<0.001**
Sidewalk buffer (Reference: None)						
One side	0.65	0.28 – 1.03	**0.001**	0.57	0.14 – 1.00	**0.009**
Two sides	0.89	0.54 – 1.24	**<0.001**	0.81	0.42 – 1.20	**<0.001**
Sidewalk maintenance	0.72	0.48 – 0.96	**<0.001**	0.53	0.27 – 0.80	**<0.001**
Sidewalk tree cover (Reference: 0-25%)						
26 - 75%	0.58	0.34 – 0.81	**<0.001**	0.94	0.66 – 1.22	**<0.001**
76 - 100%	0.76	0.29 – 1.23	**0.002**	1.29	0.75 – 1.83	**<0.001**
Streetscape design						
Building Maintenance	0.46	0.23 – 0.70	**<0.001**	0.49	0.22 – 0.75	**<0.001**
Random Effects						
σ^2 (within variance)	2.03			2.61		
τ_{00} (Between raters' variance)	3.44_{Rater}			2.02_{Rater}		
Intraclass Correlation	0.63			0.44		
N	17_{Rater}			17_{Rater}		
Observations	848			848		
Marginal R^2 / Conditional R^2	0.195 / 0.701			0.250 / 0.577		

2.3.1 Land use

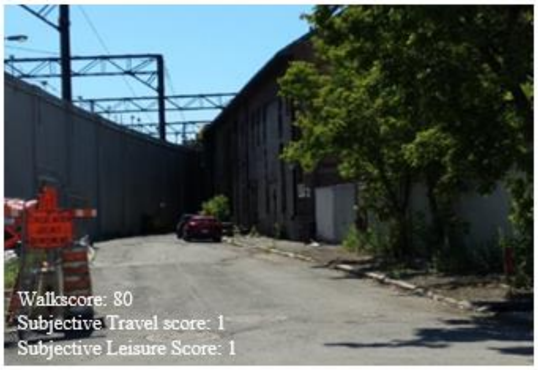
Land-use variables tested in the models included main land-use, the presence of parks, the presence of parking lots, the presence of transit stops as well as population density and residential density. However, only the first four had significant effects and solely for the model predicting leisure walking scores.

To start, a segment being characterized as vacant or industrial led to a significant decrease in leisure scores of 1.31 points compared to residential ones. This effect was expected as segments with such land-use are generally characterised by heavy truck traffic, poor aesthetics as well as noise and air pollution all of which discourage walking behavior (Herrmann-Lunecke, Mora, and Vejares 2021). The other categorization of main land use of a segment that had a significant negative effect on leisure scores was commercial which led to a decrease of 0.81 points compared to residential. This effect was also expected as predominantly commercial street segments can be categorized by heavy traffic across modes which has been shown in previous research to discourage leisure walking (Herrmann-Lunecke, Mora, and Vejares 2021). Lastly for the main land use variable, no significant effect was observed for segment categorized as mixed according to the significance levels derived from the Bonferroni correction. Such null and negative effects of land-use mixity and destination-rich areas respectively are in accordance with previous research that observed similar results on leisure walking, particularly for women (Inoue et al. 2010). Still, the result for mixed land-use could also be partly attributable to opposite effects pertaining to the level of mixity. Indeed, mixed segments were categorized as such in the audit data collected when there were both residential land-use and another destination type of land-use (i.e. commercial, institutional, industrial) on a segment without any of the land-use being noticeably dominant. Given that, a further breakdown of the characteristics pertaining to the level of mixity would be necessary to further evaluate this relationship.

Moving on to specific land-uses, having at least one park on a segment had a significant positive impact on leisure scores with 0.83 points while keeping all other variables constant at their means. This effect is coherent with recent research on the influence of greenspaces on walkability (Shuvo, Mazumdar, and Labib 2021). Greenspaces provide a change in the developed urban scenery which can be associated with increased perceived well-being (Herrmann-Lunecke, Mora, and Vejares 2021). Additionally, parks provide opportunities for leisure activities making them appealing for leisure walking. Next, the presence of ground level uncovered parking lots had a negative and statistically significant effect on leisure walking scores with segments that had at least one scoring 0.65 points less than those that did not have any. This coincides with previous research that found a similar correlation between the presence of parking and walking but in the context of walking for travel, as leisure walking was not considered (Boarnet et al. 2011). These effects can be explained by the functional disruptions that parking lots entries create for walking, their aesthetics as well as the lack of destinations of segments with numerous empty lots. Lastly, the presence of transit stops was also significantly associated with a decrease in leisure walking scores of 0.64 points. This finding was not expected as previous research has not found any such link and the direct mechanism of explanation is not evident. Still, the main plausible explanation for this finding is that the presence of a transit stop is indicative of a street with a busier traffic flow – an element that has previously been linked with lower perceptions of walkability (Herrmann-Lunecke, Mora, and Vejares 2021).

2.3.2 Accessibility

The only accessibility variable tested in the model was Walkscore© which only had a significant effect on subjective walking for travel scores with an increase in 0.16 points for every increase of 10 in Walkscore©. The lack of effect on leisure walking scores was expected as per definition leisure walking is discursive meaning that pedestrians are not walking to a specific destination and as such having access to destinations – which is what Walkscore© quantifies – is likely not important. Such differential results in destination diversity between walking for travel and walking for leisure were also observed in past research (Inoue et al. 2010). Further analysis was conducted to explore the relationship between Walkscore© and subjective walkability. A weak correlation for walking for travel (R^2 = 0.1368) was observed while no correlation was observed for leisure scores (R^2 = 0.0136). To explore this, segments with mismatched Walkscore© and subjective walkability scores (i.e., when the scores have opposite values) are presented in Figure 3.



a) GBL110 - Dalhousie (Ottawa / cul-de-sac)

b) CS53 - Hermine (Viger / Gauchetière)

c) IDS4 - de la Pointe-Nord (Jacques-le-Ber / Round about)

d) EM15 - Vincent-d'Indy (Willowdale / Côte-Sainte-Catherine)

Figure 3 Outlier segments with subjective scores mis-matched to their Walkscore©

Figure 3 displays pictures of streets visited and scored by raters that exemplify the limitation of areal metrics like Walkscore© in predicting walking experience at a micro-scale. Indeed, it shows that is plausible to have segments with poor perceived walkability in objectively highly walkable areas overall (e.g., segments #GBL110, CS53) or, on the opposite, segments being given high perceived walkability scores that are located in poorly accessible areas (e.g segment # IDS4, EM15). This further emphasizes that Walkscore© – which is an areal metric that assesses access to opportunities through walking – cannot on its own account for perceived walkability, especially for leisure walking for which it is not accurate at all. This coincides with previous research that attributed similar discordances between Walkscore© and walking rates to the lack of consideration for micro-scale elements such as sidewalks characteristics and tree cover (Herrmann et al. 2017).

2.3.3 Street connectivity

The only street connectivity indicator tested – cul-de-sacs – had a significant impact only on the model for travel walking scores for which it led to a decrease of 0.99 points. This finding differs from previous research analyzing walking behaviours and physical activity for travel (Boarnet et al. 2011). Still, street connectivity and the possibility to employ a street segment to go to the desired destination is a credible pathway to explain the effect observed on walking for travel. It should be noted that the homogeneity of the auditors used in this study might be reflected here. Indeed, since all auditors were working for the department of urban planning or had research experience on walkability, it is plausible that they would have been more sensitive to larger scale elements such as street connectivity when scoring each segment.

2.3.4 Safety and security

Speed limit had a statistically significant effect on both subjective walkability models as it decreased travel scores by 0.33 points and leisure scores 0.56 points per added 10km/h while keeping all other variables constant at their mean. This result aligns with previous research predicting walking behaviour using audit measures (Boarnet et al., 2011). The underlying mechanisms behind the correlation rely on the decrease of safety that comes with increased traffic speed (Suarez-Balcazar et al. 2020). Additionally, routes with higher speed limits will also tend to have denser traffic which lead to increase air and noise pollution levels, both of which have been associated with (Herrmann-Lunecke, Mora, and Vejares 2021). The next safety variable – street lighting – only had a significant impact on both models when in ample presence compared to none with an increase of 0.85 and 1.23 points for travel and leisure scores respectively. This finding aligns with previous research (Blecic et al. 2016) and it can be explained by the increased feeling of safety that proper street lighting creates (Davoudian, Mansouri, and Cie 2016). It should be noted that the relative importance of streetlighting might vary based on the time of day, an element that was not captured in the audit process as all data was collected during the day. Lastly, the presence of pedestrian light signals did not present any significant effect in either model but, as it led to an increase in the predictability of the travel model, it was kept as a suppressor variable.

2.3.5 Pedestrian facility and comfort

The presence of benches on a street segment had a significant effect in both models as it led to an increase of 0.47 points in travel scores and 0.61 points in leisure scores compared to segments without any benches. This finding is in agreeance with prior research and was expected as benches provide opportunities to rest during a walking trip (Blecic et al. 2016). With this in mind, the smaller effect on travel score is also coherent as walking of travel being purposive, stopping to sit on a bench is less likely than when walking for leisure in which no set destination has been established before the start of the trip. The relative importance of this finding might once again vary between different social groups with elderly people and people suffering from a disability that limit their mobility likely to require to stop more often during a walking trip.

Moving on to sidewalk characteristics, the presence of sidewalk buffers and the maintenance of the sidewalk both had significant effects in both models. Indeed, one-sided sidewalk buffers led to a significant increase of 0.65 points in travel scores and 0.57 in leisure scores compared to no buffers at all while having buffers on both sides of the street led to an increase of 0.89 and 0.78 points for travel and leisure walking scores respectively. This significant effect is coherent with previous research (Blecic et al. 2016, Boarnet et al. 2011) as buffers provide a separation both through added distance but also through added objects (e.g., streetlights, trees) that create an increased feeling of safety from traffic (Herrmann-Lunecke, Mora, and Vejares 2021). The impact of a sidewalk buffer will differ between a calm residential street with a low-speed limit (i.e., 30km/h) and a busier arterial road with higher speed limit (i.e., 50km/h). While the former could still be pleasant and feel safe with a narrow sidewalk to walk on, the latter will provide an increasingly stressful experience that could likely lead to pedestrian avoidance. Next, sidewalk maintenance also had a statistically significant effect on both travel and leisure scores with an increase of 0.72 points and 0.53 points respectively for segments that had no deteriorated parts of the sidewalk compared to those that did. This finding differs from previous research that found no impact on subjective walking scores (Blecic et al. 2016), while it aligns with research that worked on predicting physical activity levels from objectively-measured qualities using built environment audits (Boarnet et al. 2011) as well as past qualitative research (Bohte, Maat, and Van Wee 2009). The main mechanism to explain this finding is that well-maintained sidewalks provide a safer and more pleasant travelling environment than those with visible cracks and holes. Such effects are likely to be more important in demographics such as elderly adults and people with mobility impairments (Herrmann-Lunecke, Mora, and Vejares 2021) which were not captured in the rater population used for this study meaning that the strength of the effect measured in the models might be lower than that of the population as a whole.

Lastly, walkway tree cover was also a statistically significant predictor of both scores with 26 – 75% cover leading to an increase of 0.58 and 0.94 points and 76 – 100% cover leading to an increase of 0.76 and 1.26 points compared to a tree cover of 0 – 25% for travel and leisure subjective scores respectively. This finding is coherent with past research predicting subjective walkability (Blecic et al. 2016) as well as assessing mediators of the relationship between socio-economic status and walking for travel (Cerin, Leslie, and Owen 2009), but it differs from research that predicted walking behaviour with built environment characteristics (Boarnet et al. 2011). Discrepancies between results observed here and those of previous research using objective walkability measurements might be extrapolated as a reflection of captive pedestrians that do not have a choice to walk on routes they do not perceive as very walkable for travel. Recent research contrasting greenness and walkability in a large metropolitan context established that areas are rarely both green and objectively walkable, with suburban areas being often greener but less walkable and urban areas being less green but more walkable (Shuvo, Mazumdar, and Labib 2021).

2.3.6 Streetscape design

The only streetscape design element that had a significant outcome in the models was building maintenance with street segments having solely well maintained buildings having scores 0.46 points and 0.49 points higher for walking for travel and leisure respectively. This finding differs recent literature suggesting building aesthetics are not important predictors of walking for travel (Boarnet et al. 2011). The potential pathway of explanation behind this finding might be linked to poorly maintained buildings being associated with a reduced feeling of security – likely through associations with criminality

– or building in construction being associated with heightened levels of stress likely from the repairs being conducted (Herrmann-Lunecke, Mora, and Vejares 2021).

2.4. DISCUSSION

Overall, this study highlights differential results between determinants of perceived walkability for walking for travel and walking for leisure primarily regarding the influence of land-use density and mixity which is on par with past research (Boarnet et al. 2011, Hsieh and Chuang 2021, Inoue et al. 2010, Inoue et al. 2011). The negative effect observed between commercial land-use and perceived walkability for leisure as well as the lack of effect of mixed-land use on the later suggest that a focus on destination-rich land-uses as promoting walking is likely not sufficient to understand walking experience itself. The same can also be said for the minimal effect of Walkscore© on perceived walkability for travel as well as its lack of effect for leisure walking. These findings are particularly relevant when considering that all raters had previous knowledge of the urban planning and walkability literature. Indeed, one would then expect if there was to be a bias introduced through the homogeneity in educational background, that the raters would value commercial and mixed streets higher than residential ones because they provide more destinations – an element commonly emphasized in the urban planning and walkability literature. As such, the fact that we are observing the opposite effect in the case of leisure scores and weak effects for travel scores suggests that the factors commonly considered to evaluate walkability objectively and at the areal level are not necessarily adequate to explain walking experience at the micro-scale level which is coherent with past research (Battista and Manaugh 2017, Gebel, Bauman, and Owen 2009, Koohsari et al. 2021, Tuckel and Milczarski 2015, Yang and Diez-Roux 2017). Observed levels of walkability might differ from subjective scores in the case of areas with a high density of destinations such as a downtown core. This could reflect what can be defined as “captive walkers”, people that are forced to walk in a certain area for travel purposes, but that do not perceive the environment in which they walk as highly walkable (Suarez-Balcazar et al. 2020).

Walkability is more than solely walking accessibility; it also incorporates elements pertaining to walking experience. This experience itself is a result of the interaction between pedestrians and their walking environment, both physical and social, and as such cannot be understood as solely objective. In fact, features of the walking environment can shape emotional responses that in turn can promote or deter walking in certain areas (Herrmann-Lunecke, Mora, and Vejares 2021, Ortiz-Ramirez, Vallejo-Borda, and Rodriguez-Valencia 2021). Functionality and pleasantness of elements of the built environment do not necessarily align across socio-demographic groups and even less so at the individual level. This consideration is important to integrate here given the limitation of this paper in term of the demographics of the raters. The homogeneity of raters, especially in terms of age and education levels entails that the significance of specific features of the built environment on perceived walkability might not be representative of the population as a whole with elements such as sidewalk states and benches having potentially a stronger importance in an older demographic while element such as cul-de-sacs are likely not as relevant for the broader population. Still, the pathways of action discussed in this paper in relation to the specific predictors of the built environment included in the models are relevant considerations to have as they are likely to be relevant for a specific subgroup of the population given the high variability of individual preferences. While no significant differences in the mean subjective walkability scores were found between raters identifying as men or women, the small number of raters ($n = 17$) meant that the models could not be disaggregated by gender to explore the differential influence of each predictor. As such, we would strongly encourage replication of this study with a larger and more diverse number of raters completing only the subjective scoring to be able to infer any generalizable trends at the population level. We would also suggest disaggregating along socio-demographic characteristics (e.g. gender, age, income, (dis)ability) to identify variation in perceived walkability between social groups and devise policy recommendations to address potential inequities. However, given the expected variety in the psychological and emotional responses of individuals to the built and social environment while walking that have been observed in previous research (Adkins et al. 2019, Herrmann-Lunecke, Mora, and Vejares 2021), it is possible that even a slightly larger, more representative group of raters would be limited in its ability to extrapolate on population-wide trends.

Still, these considerations do not form the primary contribution that this paper aims to bring to the walkability field. Rather, we want to highlight the discrepancies discovered between walking for leisure and walking for travel for a given set of individuals as well as the discordances observed between subjective and objective walkability as the two primary components for which this study can help advancing the field. Recognizing variability in perceptions of the built environment and its suitability for walking based on trip purpose could further contribute to better understanding the specific determinants of walking for leisure and walking for travel and tailor specific interventions according to the type of walking that is aimed to be promoted. Additionally, we want to stress the need to move away from solely using objective and areal measurement to assess walkability which often has the result of conflating walking accessibility with walkability as a whole. Walkscore© and other similar walkability indices should not be discounted totally on the basis that they do not align with perceived walkability as they still provide crucial information about the built environment which shape the possibility to take a walking trip in the first place. However, whether individuals will or will not take a certain walking trip is not solely a matter of whether they *can* but also whether they *want* to. This latter addition introduces an element of subjectivity that must be considered in walkability research to achieve a better understanding of walking behavior. Subjective walkability measurements can be used here to explore the factors behind discordances between walking rates predicted through objective walkability measurements and observed rates.

Overall, this paper positions itself as a contributor to the necessary reframing of the field of walkability research and its assumptions that has been underway over the last decade (Andrews et al. 2012, Shashank and Schuurman 2019, Tobin et al. 2022). What our findings suggest is that subjective and objective walkability measures are complementary and should therefore be used together rather than separately as to construct a more complete understanding of the relationship between the social and built environment and walking behavior (Arvidsson et al. 2012, Nyunt et al. 2015). The same can also be said in relation to the scale of walkability measurements with micro and meso-scale indices quantifying different relevant aspect of the built and social environment and as such needing to be used in combination with one another to quantify the propensity of a given environment to promote walking for a diverse set of individuals.

2.5. CONCLUSION

Overall, this study emphasises the differential results in the built environment determinants of perceived walkability based on trip purpose. We also further support past research in highlighting the shortcomings of areal, objective walkability indices such as Walkscore© in predicting perceived walkability and walking experience. The focus on destination density as a main determinant of walkability should also be reconsidered as a positive predictive factor of walking accessibility, but not as a predictor of walking experience per se. Given these results, we suggest the need to integrate more readily the differentiation between walking for travel and walking for leisure in walkability research. We support previous calls from other researchers that the predictors of perceived walkability and walking experience need to be more studied and better incorporated in policy design as complements to objective measures (Blecic et al. 2016, De Vos et al. 2022, Fancello, Congiu, and Tsoukias 2020, Manaugh and El-Geneidy 2013, Moura, Cambra, and Gonçalves 2017, Tuckel and Milczarski 2015). Lastly, we argue for a multi-scalar approach to walkability by integrating micro-scale features of the street environment alongside the more common meso-scale metrics such as Walkscore© or Frank's walkability index in order to provide a more complete portrait of the complex determinants of walking behavior.

2.6 REFERENCES

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CONNECTION BETWEEN CHAPTERS

While Chapter 2 focused on evaluating the effect of micro-scale built environment elements (MAPS-Mini) and Walkscore© on perceived walkability, Chapter 3 focuses on assessing how accurately these two measures of walkability can predict probability to walk for travel. Of particular importance in Chapter 3, is the evaluation of the interactions between socio-demographic characteristics and the built-environment to assess differential effects of walkability between social groups. This could not be done in Chapter 2 due to the small and homogeneous number of raters, which prevented the subdivision of the models along socio-demographic characteristic. As such, Chapter 3 builds upon Chapter 2 by delving deeper in the subjectiveness of walkability and how it varies between socio-demographic groups.

In order to be able to conduct such larger scale analysis, it was decided, after the first wave of data collection, to expand the audit to a 1000-meter service area around each REM station. Lastly, with the experience of the first wave of data collection, changes were made to the audit questionnaire which resulted in an updated version (Appendix 2). Questions from the MAPS-Mini were left for the most part untouched between Wave 1 and Wave 2 with a few exceptions. From Wave 1 (Appendix 1), question 7 counting transit stops was removed and replaced by official data from transit agencies linked back to the street segments through GIS to minimize the introduction of error. Lastly, changes were made to offer more response options to question 7 on main land-use, question 11 on building maintenance, question 13.1 on sidewalk maintenance and question 14 on sidewalk tree covers (Appendix 2). Despite these changes, all items of the MAPS-Mini can be converted back to their original structure by aggregating the more detailed options given in the modified audit questionnaire which allows for the calculation of the score as intended by the original tool. With data collected across a larger geographical range, it was estimated that a larger sample of people would be able to fall within the audited area, allowing for the analysis of differential effect of walkability on walking across socio-demographic groups.

CHAPTER 3 – ANALYZING INTERACTIONS OF INDIVIDUALS' SOCIO-DEMOGRAPHICS WITH WALKABILITY WHEN MODELLING WALKING BEHAVIOR

Abstract: Walkability research often controls for socio-demographic characteristics in travel behavior analyses; however, this approach does not allow for the evaluation of differential impacts of features of the built environment between social groups. Using trip data from Montréal, Canada, this paper evaluates two commonly used walkability indices – Walkscore© and the MAPS-Mini audit tool – and their interactions with socio-demographic characteristics. Binary regressions are used to model the probability of adults walking to destinations as a function of trip, person, and household characteristics, as well as walkability indices for the household location. Interactions are conducted between four socio-demographic variables – gender, age, household income, and presence of children below 13 years old in the household – and each of the walkability indices. Sensitivity analyses are then conducted using the interaction outputs by varying the values of the interacted socio-demographic variable. Results show significant interactions for all variables for both indices except from Walkscore©'s interaction with gender. Opposite effects are observed between the two indices in the sensitivity analysis for household income and presence of children. These findings highlight the need to consider socio-demographic factors when evaluating walkability and will be of value for transport professionals as they work towards generating equitable and walkable environments.

Keywords: Walkability, Walking, Socio-demographic, Gender, Age, Equity, Walkscore©, Audit, Built Environment

Highlights:

- Interactions between socio-demographic characteristics and walkability are tested
- Walkability impacts individuals differently based on their socio-demographics
- Different walkability indices do not interact similarly with all socio-demographics
- MAPS-Mini better explains expected gender differences in walking behaviors
- Both indices explain similarly the effect of age on walking behaviors
- Walkscore© better explains expected income-based differences in walking behaviors

3.1. INTRODUCTION

The concept of walkability encompasses a wide range of attributes of the natural, built, and social environments. The way researchers and policy makers conceive of this concept reflects different preoccupations and policy goals, leading to a plurality of definitions that can often be incongruent with one another (Forsyth, 2015; Shashank & Schuurman, 2019). Broadly speaking, walkability can be conceptualized as the subcomponent of Active Living Environments (ALEs) focusing on walking (Tobin et al., 2022). It represents a variable set of components of the physical and social environment that can promote walking as a mode of transportation (i.e. purposive walking) or as an activity in itself (i.e. discursive walking). The assessment of walkability usually has one of two goals: (1) understanding the features that promote or support increasing walking trips – which can be done through densification and diversification of land-use, higher accessibility and improved connectivity – or (2) understanding how to improve the walking experience (i.e., the pleasantness of the walk, feeling of comfort or security) – which can be usually realized through changes in the pedestrian environment (e.g., sidewalks, crosswalks, tree cover) (Rodrigue et al., 2022) or social interventions (e.g., crime reduction).

For both of these objectives, the relative importance of factors contributing to walking behavior varies with socio-demographic characteristics. Indeed, past research has shown that walking behaviours vary with gender (Hidayati et al., 2020), age (Stafford & Baldwin, 2018), income (Manaugh & El-Geneidy, 2011) and multiple other socio-demographic and socio-economic factors. While these differences have been conceptualized as the moderating effect of one's socio-demographic characteristics on their interaction with the built and social environment (Liao, EW van den Berg, van Wesemael, & A. Arentze, 2020; Manaugh & El-Geneidy, 2011) which relates to the subjective nature of walking (Consoli et al., 2020; Jun & Hur, 2015), such considerations remain very limited in walkability research overall as socio-demographic characteristics are often treated as control variable status. A large proportion of the current scholarship has focused on improving walkability through general, area-based interventions, aimed at increasing walking rates without considering the impact of socio-demographic characteristics, which can lead to oversight of subjective differences in perceptions of the safety, comfort and pleasantness of the built-environment between social groups and potentially widen existing inequities (Hall & Ram, 2018; Manaugh & El-Geneidy, 2011; Shashank & Schuurman, 2019). Contrastingly, a growing body of literature has highlighted that interventions targeted at the micro-scale environment – which more directly impacts the walking experience – can help reduce observed differences in walking behaviour between social groups (Clifton & Livi, 2005; Jensen et al., 2017; Lee & Dean, 2018).

Given the potential of pedestrian interventions to impact equity outcomes such as streetscape interventions increasing walking for women more than for men (Jensen et al., 2017), it is important to assess how the built-environment interacts with socio-demographic characteristics to influence walking behavior and whether different walkability indices have different levels of interactions. To do so, we model and contrast how socio-demographic variables interact with two commonly used walkability indices – one at the micro- and one at the meso-scale – in promoting purposive walking (i.e., walking to a fix destination). We aim to highlight the varied impact of walkability across different socio-demographic groups and the differential effects of walkability indices at the micro- and meso-scale. The main research question this paper aims to answer is: *does micro and meso-scale walkability explain differences in walking behavior across people of different ages, gender, income and household composition?* With this study, we aim to emphasize the need to shift away from walkability as centered primarily on promoting purposive walking rates towards walkability as a multi-scalar, inherently subjective concept that is influenced by individuals' socio-demographic characteristics.

3.2. LITERATURE REVIEW

Walkability research has been and continues to be animated by debates surrounding the exact definition of the concept of "walkability", what elements it should consider and what goals it should represent (Forsyth, 2015; Tobin et al., 2022). While a sizable part of the scholarship has been dedicated to meso-scale measures aimed to understand determinants of walking rates these metrics have shown to be limited in their ability to accurately predict walking rates (Consoli et al., 2020; Hall & Ram, 2018; Herrmann, et al., 2017; Shashank & Schuurman, 2019; Tuckel & Milczarski, 2015) or to capture the subjective experience of walking (Consoli et al., 2020; Jun & Hur, 2015; Tuckel & Milczarski, 2015). These findings are even more relevant when differentiating between purposive (i.e. utilitarian) and discursive (i.e. leisure) walking (Steinmetz-Wood et al., 2020; Wasfi, et al., 2017). A first path explaining these issues has been the lack of consideration of street micro-scale characteristics in these metrics (Herrmann et al., 2017; Pikora et al., 2003). Such elements of the built-environment have been shown to impact pedestrian behavior both in term of walking rates but also primarily through their walking experience (Clifton & Livi, 2005; Jensen et al., 2017; Lee & Dean, 2018). These data are usually collected through built environment audits with the most popular tools used being the Irvine Minnesota Inventory (Boarnet et al., 2011; Day, et al., 2006) and the MAPS audit tool (Daley et al., 2022; Sallis et al., 2015). Built environment audits collect data on the presence and quality of features of the built environment (e.g., presence of sidewalks, size of sidewalks, level of maintenance of buildings) and can also, in some cases, additionally report elements pertaining to usage of the built environment (e.g., social interactions, number and characteristics of road users) (Boarnet et al., 2011; Day, et al., 2006; Sallis et al., 2015). Still, even these tools present limitations in accurately predicting walking rates, once again more so for leisure walking (Boarnet et al., 2011; Sallis et al., 2015).

A growing scholarship on subjective or perceived walkability has argued for increased consideration of pedestrian perceptions – which are dependent on personal characteristics – as crucial moderating factors of walking behaviour which makes improve travel behavior models (Adkins, Barillas-Longoria, Martinez, & Ingram, 2019; Consoli et al., 2020; De Vos, Lättman, van der Vlugt, Welsch, & Otsuka, 2022; Herbolsheimer et al., 2020; Jun & Hur, 2015; Moura, Cambra, & Gonçalves, 2017). Recent literature has highlighted a disconnect between common objective walkability measures and pedestrians' perceived walkability (Rodrigue et al., 2022; van der Vlugt, Curl, & Scheiner, 2022). Other recent research has also applied new theories of environmental psychology like the Mehrabian and Russell model to walking, finding that the effect of walking environments on travel behaviours is moderated by pedestrian's emotional and psychological reactions which are in turn dependent on personal characteristics (Ortiz-Ramirez, Vallejo-Borda, & Rodriguez-Valencia, 2021). As such, to better understand the variability in walkability tools' ability to predict walking rates, characteristics of the pedestrians must also be considered given their influence on individual perceptions of the built environment.

While socio-demographic variables have been used as control variable in several studies employing walkability measures, their mediating or moderating effects on the relationship between the built and social environment and walking behaviour has still to be readily explored (Hall & Ram, 2018; Manaugh & El-Geneidy, 2011). In term of income, people with lower incomes have been shown to be more likely to walk in areas with low local accessibility to destinations by walking, exemplifying a weaker effect of the built environment on their walking behavior (Manaugh & El-Geneidy, 2011; Steinmetz-Wood & Kestens, 2015). Past research has also highlighted how high-income areas benefit from higher quality streetscapes than low-income areas at equal level of local accessibility (Koschinsky, Talen, Alfonzo, & Lee, 2017) and how high-level of physical walkability are associated with heightened socio-economic distress in local residents (Jun & Hur, 2015).

In term of gendered differences, past studies have shown mixed effects in term of correlation between meso-scale walkability and women's level of walking (Kelley, Kandula, Kanaya, & Yen, 2016; Twardzik et al., 2019) while improvements in the micro-scale built environment have been linked to increased walking trips (Jensen et al., 2017). These effects can be attributed to women being more likely to allocate more importance towards perceived safety – both in term of crime and traffic – in their decision to walk or not (Clifton & Livi, 2005; Hidayati et al., 2020). This gendered difference has been partially attributed to women being more socially conditioned to be risk-averse than men (Shirgaokar, 2019). Gendered distribution of mobilities of care have also been highlighted as limiting factors to women's mobility options, impacting primarily their ability to use active transport. Despite the increased level of women in the work force, this one-sided distribution of care tasks still persists today which adds an additional constraint on women's mobility as they have to reconcile commuting with care trips on a daily basis (Craig & van Tienoven, 2019; Grant-Smith, Osborne, & Johnson, 2017; Ravensbergen, Fournier, & El-Geneidy, 2022).

In relation to age, older adults have been associated with higher risk of fatality in car-pedestrian collisions due to their increased vulnerability (Buehler & Pucher, 2017).

Consequently, past research has highlighted lower prevalence of walking among older adults (Curl & Mason, 2019; Riggs & Sethi, 2020; Stafford & Baldwin, 2018; Wasfi et al., 2017) with differential impacts of the built environment being observed between age groups (Liao et al., 2020; Stafford & Baldwin, 2018). Fear of falling (Curl, Fitt, & Tomintz, 2020), avoidance of risky or uncomfortable environments (Dean et al., 2020) as well as extreme urban density and land-use mix (Cheng, De Vos, Zhao, Yang, & Witlox, 2020) have all been negatively associated with older adults' walking behaviors while micro-scale features such as tree cover and sidewalk conditions have been positively linked to walking behavior for this demographic (Lee & Dean, 2018).

Lastly, many studies have highlighted how the primary limiting factors that dictate active transport behavior in children and subsequently other household members, are parents' fears and concerns, not walkability (Carver, Timperio, & Crawford, 2013; Chillón et al., 2014; Curtis, Babb, & Olaru, 2015; Foster, Villanueva, Wood, Christian, & Giles-Corti, 2014; McMillan, 2007; Ye, Gao, Juan, & Ni, 2018). Perceptions that driving is more convenient and essential when travelling with children has been highlighted as common amongst parents (Lang, Collins, & Kearns, 2011; McLaren, 2018) leading to the presence of children in the household being correlated with car ownership, a factor that has been shown to have a negative effect on active transport behavior (Curl & Mason, 2019; Ye et al., 2018).

Given the limited consideration of socio-demographic and socio-economic conditions of pedestrians in walkability research, this paper aims to contribute to the existing literature by identifying differences between social groups in the impact of the built environment as quantified by two different walkability measures on walking behavior. Additionally, by contrasting the interaction between these meso and micro scale measures with pedestrian socio-demographics in the relationship with purposive walking, we aim to further differentiate the applicability of these different walkability measures to promote equity in walking interventions. Doing so will be of value to researchers and practitioners in the transport field as they aim to use the appropriate tool(s) – or combination of tools – to identify areas of interventions that could result in the decrease of inequities in walking rates.

3.3. METHODOLOGY

3.3.1 Data

Data for this study was collected in Montréal, Canada. Two commonly used walkability measures, Walkscore© and the MAPS-Mini audit tool, were used to represent objectively measured meso- and micro-scale walkability respectively. Walkscore©, which is a composite index reflecting block length, intersection density and gravity-based accessibility to a fix set of destination (Hall & Ram, 2018) is one of the most commonly used meso-scale walkability index in the academic literature thus justifying its choice. The MAPS-Mini Audit tool is a validated street level audit tool commonly used by public health professionals – which describes features that pedestrians directly interact with while walking (Daley et al., 2022; Sallis et al., 2015). The MAPS-Mini audit tool therefore presents the opportunity, in theory, to be able to reflect factors influencing both purposive and discursive walking behaviour but primarily in term of walking experience. Given the resource-extensive process required to collect micro-scale built-environment data, the study relied on existing data collected using the MAPS-Mini audit tool as part of a built environment audit conducted in a 1km service area around the stations of the upcoming Reseau Express Metropolitan (REM) a new light-rail train (LRT) system in Montreal, Canada. Service areas were used to represent a realistic 'walkshed' (i.e., the area around a location within which people are expected to be able to walk to the location) around each station. In total, 2,497 street segments were audited using an adapted version of the MAPS-mini audit tool. Data collection took place between May 25th to July 1st, 2021, and May 5th and June 10th, 2022 and required a total of 650 hours from 18 auditors who were all trained prior to the audit on the collection of the objective data.

Trip level data from the 2018 Montréal Origin-Destination (O-D) survey was used in the analysis. The O-D survey, which is conducted every five years by the regional public-transit planning agency in the Montréal Metropolitan Region collects a travel diary record covering all household members trips on the previous day for a random sample of 5% of households in the region. Expansion factors – which are weights assigned to each observation in a dataset to allow to expand the sample at the population level – are then derived for each trip, person, and household to allow for representative analyses.

Trips from the O-D survey were filtered to get to the final sample. Out of all the trips recorded in the O-D survey (n=393,826) all those conducted by modes other than walking, cycling, public transit, or car (i.e., school bus, inter-regional buses, other) were removed (n=16,910) were removed since accurate travel times could not be calculated (Birkenfeld et al., 2023). Then, only trips from households falling within the 1-kilometer service areas around the REM stations (Figure 1) were selected (n=9,769). For each variable of interest obtained from the O-D survey (Table 4; 5), trips that did not report a usable answer (n = 2,396) were removed from the sample. Additionally, children below 18 (n=801) were also removed as factors influencing their propensity to walk have been shown to differ from adults (Chillón et al., 2014; McMillan, 2007) which could affect the relationship between age and the built environment. A trip chaining dummy variable was then derived based on whether the trip in question was part of a succession of trips starting each from the end location of the previous one. From there, trips were then filtered to keep only those that started at the home location (n=2,964). Lastly, one trip was randomly selected for each person to avoid having them appear more than once in the sample leading to a final sample of 2,352 walking trips.

Using the final sample of trips, a weighted average of the MAPS-Mini score was calculated using all audited streets reachable in a 400-meter network distance from the home location. It was assumed that the audited streets were representative of the neighboring built environment. The MAPS-Mini audit score – a score between 0 and 21 – was then weighted based on the total length of each street segments and averaged. Values were subsequently normalized using the maximum value in the sample to correct the left-sided skewness of the data. For Walkscore©, values at the household location were collected through the online API. Both MAPS-Mini and Walkscore© values were converted to be on a scale from 1 to 10 to allow meaningful comparison. Walking travel times were also calculated for each O-D pair – no matter what mode was actually used for the trip – along the street network, obtained from open street maps, using the routing package r5r (Pereira, Saraiva, Herszenhut, Braga, & Conway, 2021) in R with a walking speed of 4.5 kilometer/hour (Silva, da Cunha, & da Silva, 2014). Trip purpose data from the O-D survey were aggregated as being either work, school, shopping or other. Household level characteristics considered included household size, the number of cars, as well as the presence and number of children in the household. Household income which was reported in $30,000 increments in the O-D survey was also used, but for the purpose of the statistical models, it was combined into five classes. Complete descriptive statistics of the sample are displayed in Table 4 (continuous variables) and Table 5 (non-continuous variables).

It should be noted that the O-D survey has been recording sex, not gender, since it first inception in the 1970s. However, the primary pathways explored to explain the observed difference between women and men in travel behaviors are mostly structured around the social construct of gender and not biological sex differences (Clifton & Livi, 2005; Hidayati et al., 2020; Ravensbergen et al., 2022; Shirgaokar, 2019). As such, while the available data only records sex, since 99.67% of the Canadian population identifies as cis-gendered (Statistics Canada, 2022), we assumed gender to be concordant to self-declared sex for this analysis. The implications and limitations of this assumption will be discussed at the end of the paper. Lastly, while age and walking travel times are reported in years and minutes respectively in Table 4, they where both divided by 10 in the statistical regression models resulting in coefficient reported being for marginal increases of 10 years in age and 10 minutes in walking travel times.

3.3.2 Analysis

Expansion factors derived from socio-demographic and travel flow data are used in travel behaviour surveys to weight the sample to the broader population and ensure its representativeness. Using the trip-level expansion factors from the O-D survey, weighted binary logit models were computed in R to model the probabilities of having taken a home-based trip by walking. It was decided to use a single-level model given the goal of the analysis to assess the influence of individual, household and built environment characteristics on walking propensity, which is not possible when observations are nested within individuals or households (Manaugh & El-Geneidy, 2011). In order to evaluate the differential effect of local accessibility and the micro-scale built environment across person and household level characteristics, interactions variables were modelled between the characteristics of interest and the walkability indices used – Walkscore© and the MAPS-Mini audit tool. Each interaction was inputted into a separate model using the same set of control variables present in the original models. For each interaction variables, a sensitivity analysis was generated by varying the value of the interacted socio-demographic variable (e.g., different ages, household income levels). All other independent variables were fixed at their mean except for walking travel time which was fixed at 15 minutes to reflect a realistic walking time. Walking rates were then calculated and graphed for each interaction variables.

3.4. RESULTS

Descriptive statistics of the continuous and categorical variables included in the models are presented in Table 4 and Table 5 respectively. The normalized Walkscore© and the normalized Maps Mini score for the sample have comparable means (5.82 and 5.34 respectively). 14.2% of the trips included in the models were conducted by walking.

Results from the base linear logit model (Table 6) reveal that all predictors included had a statistically significant effect at the 5% level on the probability of taking a homebased trip by walking and that the directionality of these effects were the same between both models regardless of the walkability index used. Walkscore© allowed for a slightly better fitted model (R^2 = 0.480) than the MAPS-Mini audit tool (R^2=0.464), but the difference is small.

In terms of trip characteristics, the odds of taking a trip by walking were 51% higher for work trips than for other utilitarian trips in the Walkscore© model and 66% higher in the MAPS-Mini model, ceteris paribus. School trips have 16% lower odds of being done by walking for the Walkscore© model and 20% lower in the MAPS-Mini model compared to other utilitarian trips, holding other things constant. Similarly, compared to other utilitarian trips, the odds of home-based shopping trips to be conducted by walking were 11% lower for the Walkscore© model and 20% lower in the MAPS-Mini model. Every increase in walking travel time of 10 minutes led to odds of walking 57% lower for the Walkscore© model and 59% lower in the MAPS-Mini model, holding other variables constant at their mean. Lastly, odds of a trip being conducted by walking were 52% lower for the Walkscore© model and 54% lower in the MAPS-Mini model if the trip was part of a trip chain compared to if it was not, ceteris paribus.

Table 4 Descriptive statistics of continuous model variables

Variables	Mean	Min	Max
Trip-level characteristics			
Walking travel time [Minutes]	90.93	3.00	200.00
Person-level characteristics			
Age [Years]	48.96	18.00	96.00
Household-level characteristics			
Household size [Count]	2.65	1.00	7.00
Household cars [Count]	1.41	0.00	6.00
Walkability indices			
Walkscore [Normalized]	5.82	0.20	10.00
MAPS Mini Score [Normalized]	5.34	0.00	10.00

Table 5 Descriptive statistics of categorical model variables

Variables	%
Dependent variable	
Trip done by walking	14.2
Independent variables	
Trip-level characteristics	
Trip Purpose	
Work	49.2
School	9.9
Shopping	12.0
Other	28.9
Trip chaining [Binary]	19.5
Person-level characteristics	
Gender [Women]	50.3
Household-level characteristics	
Presence of children under 13 [Binary]	20.7
Household Income	
$0 - $30,000	12.5
$30,000-$60,000	21.3
$60,000-$90,000	18.7
$90,000-$150,000	24.4
$150,000 +	23.2

For person level characteristics, women had odds 16% lower than men to be taking a walking trip in the Walkscore© model while these odds were 19% lower in the MAPS-Mini model. Odds of taking a trip by walking were also lowered by 19% for the Walkscore© model and 23% for the MAPS-Mini model for every increase of 10 years in age.

For household characteristics, every added person led to a reduction in odds of walking of 5% in the Walkscore© model and 13% in the MAPS-Mini model. Every added car accessible in a household led to a reduction in odds of walking by 42 % in the Walkscore© model and 46% in the MAPS-Mini model, ceteris paribus. The presence of children aged below 13 years old led to a reduction in odds of walking of 38 % in the Walkscore© model and 41% in the MAPS-Mini model, holding other things constant. In term of household income, all groups were more likely to walk for a homebased trip than those in the lowest income groups by 23% to 71% in the Walkscore© model and by 23% to 95% in the MAPS-Mini model.

Finally, improvements of 1 in normalized Walkscore© values at home location led to an increase of 23% in the probabilities of taking a homebased trip by walking (OR = 1.23, 95% CI [1.21-1.25]) while an improvement in 1 of the normalized MAPS-Mini score led to an increase of 9% (OR = 1.09, 95% CI [1.06-1.12]), holding other things constant.

Table 6 Odds ratios from binary logit models predicting the probability of taking a trip by walking

	Base models		**Gender Interaction**		**Age interactions**		**Income interactions**		**Children interactions**	
Predictors	*Walkscore*	*MAPS-Mini*	*Walkscore*	*MAPS-Mini*	*Walkscore*	*MAPS-Mini*	*Walkscore*	*MAPS-Mini*	*Walkscore*	*MAPS-Mini*
(Intercept)	4.15**	18.01**	4.51**	33.46**	7.47**	83.52**	5.35**	12.22**	3.53**	14.53**
Trip-level characteristics										
Trip Purpose [Reference: Other]										
Work	1.51**	1.66**	1.52**	1.65**	1.51**	1.64**	1.54**	1.73**	1.53**	1.67**
School	0.84**	0.80**	0.84**	0.79**	0.83**	0.82**	0.81**	0.77**	0.85**	0.80**
Shopping	0.89*	0.90*	0.89*	0.88*	0.89*	0.89*	0.88**	0.90*	0.90*	0.90*
Walking travel time	0.43**	0.41**	0.43**	0.41**	0.43**	0.41**	0.43**	0.41**	0.43**	0.41**
Trip chaining	0.48**	0.46**	0.48**	0.46**	0.48**	0.46**	0.48**	0.47**	0.48**	0.46**
Person-level characteristics										
Gender (Woman)	0.84**	0.81**	0.72**	0.23**	0.84**	0.80**	0.84**	0.80**	0.84**	0.81**
Age	0.81**	0.77**	0.81**	0.77**	0.71**	0.55**	0.81**	0.78**	0.82**	0.78**
Household-level characteristics										
Household size	0.95**	0.87**	0.95**	0.87**	0.94**	0.86**	0.95**	0.86**	0.97	0.88**
Household cars	0.58**	0.54**	0.58**	0.54**	0.58**	0.54**	0.59**	0.55**	0.57**	0.53**
Presence of children under 13	0.62**	0.59**	0.62**	0.58**	0.61**	0.59**	0.64**	0.60**		
Number of children under 13									0.90	1.06
Household income [Continuous]							0.97	1.24**		
Household income [Reference: - $30,000]										
$30,000-$60,000	1.23**	1.23**	1.23**	1.23**	1.23**	1.25**			1.22**	1.22**
$60,000-$90,000	1.25**	1.35**	1.26**	1.33**	1.25**	1.35**			1.24**	1.34**
$90,000-$150,000	1.71**	1.95**	1.71**	1.95**	1.68**	1.90**			1.67**	1.88**
$150,000 +	1.38**	1.57**	1.39**	1.55**	1.36**	1.55**			1.35**	1.52**
Walkscore©	1.23**		1.21**		1.14**		1.19**		1.24**	
MAPS Mini Score		1.09**		0.99		0.85**		1.17**		1.12**
Interactions										
Gender * Walkscore			1.02							
Gender * MAPS-Mini Score				1.23**						
Age * Walkscore					1.02**					
Age * MAPS-Mini-Score						1.06**				
Income * Walkscore							1.01**			
Income * MAPS-Mini Score								0.98**		
Number of children * Walkscore									0.98*	
Number of children * MAPS-Mini Score										0.94**
R^2	0.480	0.464	0.480	0.465	0.484	0.468	0.479	0.460	0.481	0.464

Note: **p<0.01; * p<0.05

3.4.1 Gender

The interaction between Walkscore© and gender (OR = 1.02, 95% CI [0.99-1.05]) was not statistically significant ($p = 0.183$) meaning that Walkscore© has a similar effect on women and men in our model. On the contrary, the interaction between the MAPS Mini score and gender (OR= 1.23, 95% CI [1.17-1.30]) was statistically significant ($p<0.01$) meaning that a differential effect of MAPS Mini score was observed between women and men. With every increase of 1 point in the normalized MAPS-Mini score (i.e., increased micro-scale walkability), women's odds of walking increased by 23% compared to men's, signifying that women are more influenced by the micro-scale built environment than men. This is exemplified in Figure 4 with increases in Walkscore© behaving similarly across gender with probabilities lines never crossing while increases in the normalized MAPS-Mini score led to a slight decrease in walking rates for men and a major increase in walking rates for women.

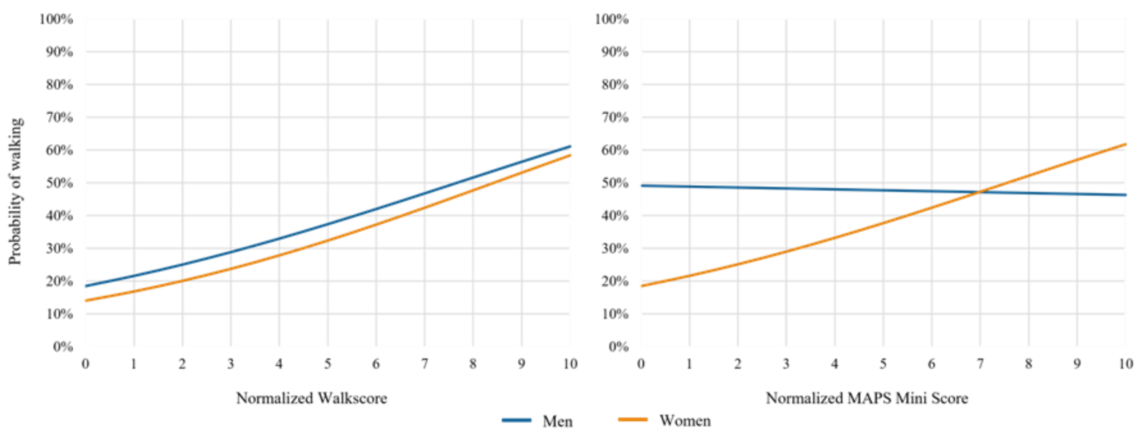

Figure 4 Predicted probability of walking from interactions between gender and walkability indices

3.4.2 Age

The interaction between age and Walkscore© (OR = 1.02, 95% CI [1.01-1.03]) was statistically significant ($p<0.01$) meaning that for every increase of 10 years in age, an improvement of 1 point in normalized Walkscore© would lead to an increase in odds of walking by 2%, ceteris paribus. Similarly, the interaction between age and MAPS-mini (OR= 1.06, 95% CI [1.04-1.07]) was statistically significant ($p<0.01$) meaning that for every increase of 10 years in age, an improvement of 1 in normalized MAPS Mini would lead to an increase in walking rates 6% larger than for someone 10 years younger, holding other variables at their mean. The positive and statistically significant odd ratios of these interactions therefore imply that both local accessibility and the micro-scale-built environment gain importance in promoting walking as adults age. Still, the convergence of the different age groups as MAPS-Mini values increase is more pronounced than the one observed for Walkscore© in Figure 5. It should be noted that for the MAPS-Mini model, walking rates are predicted to decrease for someone aged 20 years old as walkability increases. On the contrary, odds of walking increase for all ages in the Walkscore© model, albeit at different rates.

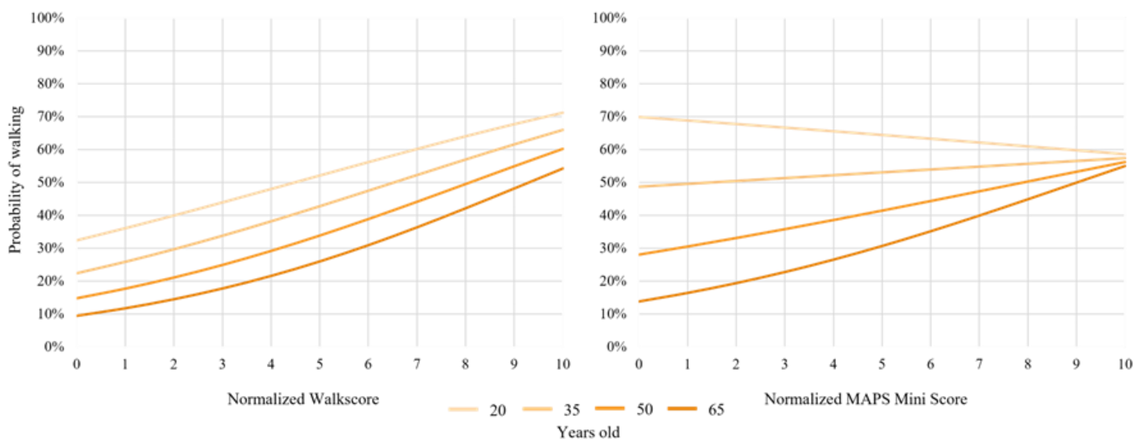

Figure 5 Predicted probability of walking from interactions between age and walkability indices

3.4.3 Household income

The interaction between household income and Walkscore© was positive (OR = 1.01, 95% CI [1.00-1.02]) and statistically significant ($p < 0.01$) meaning that every increase of $30,000 in household income will lead to an increase in odds of walking 1% larger for an improvement of 1 in normalized Walkscore©, all else equal. As such, higher income groups which start at lower walking rates in areas with poorer local accessibility will end up with the highest walking rates in higher accessibility areas (Figure 6). Nonetheless, walking rates are predicted to increase for all income brackets, albeit at different rates. For MAPS-Mini, the interaction with household income was negative (OR= 0.98, 95% CI [0.96-0.99]) and statistically significant ($p<0.01$) meaning that every increase in $30,000 in household income will lead to an decrease in walking rates by 2%. The negative significant odds ratio of this interaction implies that improvements in the micro-scale built environment promote walking more the lower one's household income is leading to the convergence of the predicted walking rates across income groups (Figure 6). It also suggests that people living in households with incomes $180K and above will see their odds of walking decrease as walkability increases.

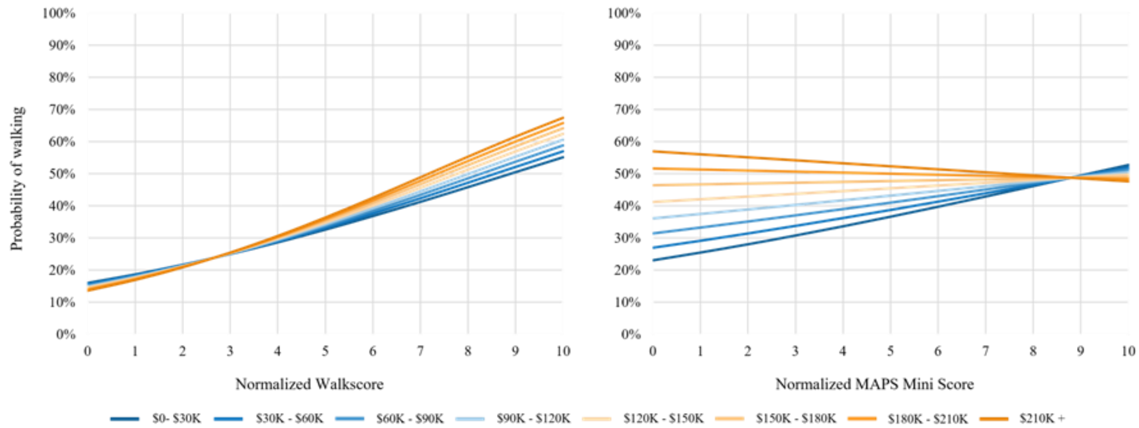

Figure 6 Predicted walking rates from interactions between household income and walkability indices

3.4.4 Number of children in the household

The interactions between the number of children aged below 13 years old in a household with Walkscore© (OR = 0.98, 95% CI [0.96-1.00]) and with the normalized MAPS-Mini score (OR = 0.94, 95% CI [0.91-0.98]) were both statistically significant ($p = 0.02$ and $p < 0.01$ respectively). This meant that for every added child under 13 in a household, the increase in odds of walking was 2% smaller per incremental increase of the normalized Walkscore© and 6% smaller for every incremental increase in the normalized MAPS-Mini score. For the MAPS-Mini model, decrease in walking rates are predicted for households with two or more children as walkability increases. On the contrary, in the Walkscore© model, the odds of walking are predicted to increase no matter the number of children in the household, albeit at differential rates. In both cases, the gap in walking rates between people with different numbers of children in the household increases as the walkability improves (Figure 7).

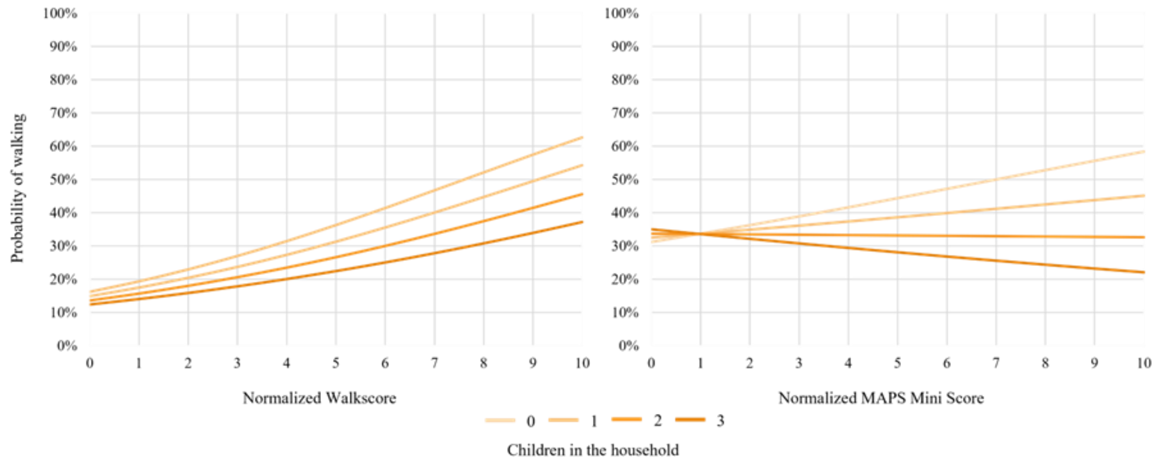

Figure 7 Predicted probability of walking from interactions between the number of children below 13 years old in the household and walkability indices

3.5. DISCUSSION

Our analysis points towards differential impacts of walkability on adults' walking behavior based on their socio-demographic characteristics, i.e., their gender, age, income, and number of children in the household. Systematic correction for socio-demographic in walking models – or even more broadly in travel behaviour models – are likely masking inequitable realities that are crucial when devising policy interventions. This study contributes to the literature by demonstrating the differential impact of walkability based on individuals socio-demographic characteristics, thus supporting previous research that called for socio-demographic to not be systematically used as solely control variables (Manaugh & El-Geneidy, 2011). This study also highlights how interactions with socio-demographics vary between the scale and measure at which walkability is assessed. This suggests that the choice of one scale or measure to assess walkability does not only have an impact on areas being targeted for interventions (Shashank & Schuurman, 2019) but could also shape which social groups benefit from ensuing interventions, thus impacting equity outcomes.

In term of interactions between gender and walkability, our analysis demonstrates differential impacts between the two indices tested. The lack of statistical significant differences between men and women for Walkscore© aligns with past research looking at the correlation between this measure and physical activity (Twardzik et al., 2019) but it goes against findings on the differential correlation of local accessibility with active transport between South Asian American women and men (Kelley et al., 2016). Conversely, the findings for MAPS-mini corroborate findings from a previous study that women's walking rates increase significantly more following street-level interventions than men (Jensen et al., 2017). This can be explained by the heightened considerations of safety – both in term of crime and traffic – that have been observed amongst women compared to men (Clifton & Livi, 2005; Hidayati et al., 2020). This has been partially attributed to the fact that women tend to be socially conditioned to be more risk-averse than men (Shirgaokar, 2019), often leading to higher levels of avoidance in environment with low perceived safety. Interventions such as proper street lighting or safe walking infrastructures – which are both considered in the MAPS-Mini audit tool – have been mentioned as potential interventions to help tackle this issue (Clifton & Livi, 2005). Still, neither walkability indices used helps explain the component of the gendered walking patterns that is attributable to mobilities of care (Craig & van Tienoven, 2019; Ravensbergen et al., 2022). This suggests that walkability as assessed through proxies of the built environment only might not be sufficient to effectively understand women's walking behavior and that more social contextualization is necessary in walkability research to better reflect gendered realities. This reality is not unique as similar limited consideration of gendered realities that move beyond descriptive male-female model outputs has also been observed in cycling research (Ravensbergen, Buliung, & Laliberté, 2019) indicating a potential issue applicable to the study of travel behaviour as a whole.

In term of age, the decrease in propensity to walk with increase in age and the positive interactions between walkability and age observed for both indices are coherent with past research which indicated that the implication of walkability varied across age groups (Liao et al., 2020; Stafford & Baldwin, 2018). The fact that increases in the MAPS-mini score promote a convergence of odds of walking across age groups suggests that the micro-scale environment might be gaining more importance through aging compared to local accessibility. This is coherent with past research that has highlighted the importance of micro-scale characteristics such as tree cover and sidewalk conditions for older adult's walking behavior (Lee & Dean, 2018). Additionally, given that older adults have been consistently associated with higher risk of fatality in car-pedestrian collisions due to their increased vulnerability (Buehler & Pucher, 2017), it makes sense that their walking behavior would be predominantly shaped by the quality of the street environment they interact with and how safe it makes them feel (Curl et al., 2020; Dean et al., 2020). As such, a shift from a predominant focus on increased local-accessibility – which has been shown to have a detrimental impact on older adults' walking rates when extremely high (Cheng et al., 2020) – towards micro-scale improvements of the built environment could promote equity across age groups and help alleviate the reduction of walking rates with age. That being said, the observed decrease in predicted walking rates for younger adults when interacting age with the MAPS-Mini score could indicate that this relationship is non-linear as it could also present potential limitations with that tool to predict purposive walking rates.

For household income, the differential results of the interactions with walkability point to potential limitations of one of the indices used. Indeed, the observed reversed effect of the MAPS-Mini audit tool on walking rates across income groups and the predicted decrease in walking rates for higher income bracket do not align with the literature. As shown for local accessibility measures in past studies, it would have been assumed that lower income individuals would walk more in areas with poor micro-scale environments due to a lack of accessible travel alternatives both financially and geographically (Manaugh & El-Geneidy, 2011). The contradictory nature of the interaction between income and the micro-scale built-environment with the current literature could be attributed to a lack of research analyzing the interaction between walking rates and micro-scale walkability that integrate income considerations. Indeed, while low micro-scale walkability mostly aligns with car-centric suburban settings which tend to be higher income (Daley et al., 2022), past research has also shown that people in low-income areas are reporting poorer micro-scale environments in term of esthetics, perceived safety or walking infrastructure (Sallis et al., 2011). These seemingly contradicting realities point towards a need for disaggregation of micro-scale characteristics forming the MAPS-Mini audit tool to evaluate their spatial distribution and individual contribution to walking behaviors. It could also point toward the limitation of micro-scale indices to reflect income differences in walking behavior. Conversely, the effect observed for the interactions between Walkscore© and household income is coherent with past research that found that low-income groups tend to walk more in areas with a low Walkscore© (Manaugh & El-Geneidy, 2011). Previous studies further highlighted that local accessibility measures have a weaker effect on lower income groups (Steinmetz-Wood & Kestens, 2015) with this reduced effect being potentially attributable to increased gentrification given that high-level of physical walkability have been associated with heightened socio-economic distress in local residents (Jun & Hur, 2015). As such, while the interactions between Walkscore© and household income is in line with theory and past research, it remains proof that interventions aimed at promoting local accessibility could lead to heightened inequities as has been stressed for this index before (Manaugh & El-Geneidy, 2011).

When looking at the presence of children in the household, the negative effects observed of additional children on adult's walking rates are coherent with past that highlighted parental perceptions of safety both in term of criminality and traffic as more important factors in children's mobility, and therefore their own, then walkability in itself (Chillón et al., 2014; Curtis et al., 2015; Foster et al., 2014; Lang et al., 2011; McLaren, 2018; McMillan, 2007). To that aspect, both Walkscore© and the MAPS-Mini audit tool reflect the expected differences in walking rates expected between the people living with young children and those that do not. Still, both measures are limited in orienting interventions to better promote walking in parents with young children. While broader interventions such as the securitization of neighborhoods – both objectively and subjectively – and educational campaigns on safe walking habits have been mentioned in the literature as potential pathways of action (Carver et al., 2013; Lang et al., 2011; McMillan, 2007), further research specifically on children walking behaviour would be need to evaluate their effect and how they might modify the interaction between walkability and walking for young children and their families. It is also important to note that the decline in walking rates observed for adults living in households with two or more children in the sensitivity analysis conducted with MAPS-Mini might be once again indicative of a potentially non-linear relationship or a limitation in the ability of this index to predict utilitarian walking given the incongruent nature of this finding with the literature.

As with any study, ours also has limitations some of which were previewed in the methodology when discussing characteristics of the Montreal O-D survey. First, the assumption that had to be made of gender corresponding to sex due to the lack of differentiation in the O-D-survey means that some respondents will have been misclassified in the analysis as they were in the data itself. Additionally, the O-D survey does not provide any information on ethnicity, immigration status or (dis)ability which are relevant socio-demographic characteristics that could have impacts on interaction with walkability and therefore walking behavior. Future iterations of this survey should include such considerations among others to allow for more thorough and inclusive research of travel behaviors. Furthermore, it should be noted that the time-consuming process of collecting the MAPS-Mini audit tool, represents a major limitation to conducting such a study on a larger scale. The constraint of the study area has limited the sample size meaning that sub-samples based on the intersection of multiple socio-demographic factors were not possible even though such interactions have been shown to be important (Kelley et al., 2016; Ravensbergen et al., 2022). Additionally, the data used in this study is for purposive walking and therefore cannot be extrapolated for discursive walking which remains understudied due to a general lack of data. Finally, the interactions highlighted in this paper are from a higher-income country perspective which is important to acknowledge as interactions between socio-demographic and socio-economic variables with the built environment and walking behavior varies based on the regional context (Shirgaokar, 2019).

Lastly, our analysis highlights limitations with the indices considered. Indeed, while the MAPS-Mini audit tool provides more detailed data that has been linked with differential perceptions of the built environment between social groups (Clifton & Livi, 2005; Jensen et al., 2017; Lee & Dean, 2018), it is seemingly not as effective at predicting walking rates compared to Walkscore©. In fact, it is possible that the predicted decrease in walking rates for specific demographic in the sensitivity analyses (i.e. men, 20 year olds, highest income brackets and people with more than two young children in the household) and the contrary direction of the finding for the interaction with household income could be attributable to the socio-demographic characteristics being stronger contributors to the interaction than the MAPS-Mini score. As such, it might be necessary to go back into each items forming the MAPS-Mini audit tool to evaluate their relevance to different social groups. As for Walkscore©, while it was shown to be more efficient in predicting purposive walking rates, interventions centered around solely the aspect of walkability that it considered (i.e. land-use and connectivity) are still at risk of increasing inequities in access to suitable walking environments, primarily across income groups and between households with and without children.

3.6. CONCLUSION

Overall, this paper highlights the importance of considering individuals' socio-demographic characteristics when assessing the impact of the built environment on purposive walking rates. People have differential interactions with the built environment based on their own socio-demographic and socio-economic status. As such, over-simplifications of the complex nature of walking behavior as the product of walkability proxies without contextualization of the individual's socio-demographic characteristics can lead to increased inequities. We therefore strongly recommend that demographics – while not a characteristic of the walking environment – be integrated not as controls but as variables having an interactive effect with the built environment in walking behaviour models, but also more broadly in travel behaviour research. Intersectionality of those characteristics should also be considered. Through our comparison of two walkability indices at different scales, we support calls from previous studies that the choice of walkability indices and what is considered to be walkable should be more theoretically grounded (Forsyth, 2015; Shashank & Schuurman, 2019). Lastly, in order to more fully understand walking behaviours, more data and research needs to be conducted on discursive walking.

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CHAPTER 4 – DISCUSSION

In this research, I aimed to assess how micro-scale walkability relates to (1) perceived walkability and (2) variations in walking rates between socio-demographic groups while also contrasting it to commonly used meso-scale indices. In doing so, I highlighted the importance of considering perceptions and socio-demographic characteristics as moderating factors of the relationship between the built environment and walking behaviour. The differential findings between social groups observed in Chapter 3 reinforces the need for additional research on perceived walkability similar to the one conducted in Chapter 2 but with a larger and more diversified sample. Indeed, if interactions with walkability indices vary between social groups as was shown in Chapter 3, this might be attributable to differential interests and priorities in term of pedestrian environments as has been shown in previous research (Hidayati, Tan, and Yamu 2020, Stafford and Baldwin 2018, Clifton and Livi 2005, Lee and Dean 2018, Adkins et al. 2019, De Vos et al. 2022). As such, being able to capture perceived walkability through a combination of methods, analyze how it is impacted by elements of the built and social environments and evaluate how these interactions vary between individuals will be crucial for the field of walkability research moving forward. Such questions fall within the scope of ongoing efforts to reframe walkability as more than prescriptive guidelines for the built environment but rather a nuanced concept that is intrinsically linked to local and personal considerations (Tobin et al. 2022).

Such increased nuancing to include more on social contexts and personal perceptions is also present across the entire field of travel behaviour. Indeed, an increasing body of research has been dedicated to understanding people's satisfaction with their mode of travel and the environment they interact with while travelling (Carvalho dos Reis Silveira, Romano, and Gadda 2020, De Vos 2019, De Vos et al. 2016, Abenoza et al. 2017). Such considerations are becoming even more important when considering the COVID-19 pandemic and the drastic changes it has created in daily transportation patterns (Buehler and Pucher 2021, Mouratidis and Papagiannakis 2021, Palm et al. 2022). With telecommuting being expected to remain at a larger proportion post-pandemic than it was before the pandemic (Frumkin 2021), a shift in paradigm to active and public transportation interventions is imminent. Indeed, with more flexibility in working hours and working location, people who took transit or used active transportation because they were forced to (i.e., captive riders and captive pedestrians) will have, in many cases, reduced incentives to travel in undesirable conditions, thus leading them to conduct fewer trips overall. As such, I hypothesize that trip satisfaction and individual perceptions might become more important in the decision making of individuals if they have increased choice to conduct a trip or not. Characteristics of the home location might as well gain more importance in explaining active transportation behavior for less mobile individual (i.e. works remotely instead of commuting to the office) (Victoriano-Habit and El-Geneidy 2023). Understanding elements that influence trip satisfaction is therefore increasingly important, particularly to inform adequate policy to promote public and active transportation.

In the case of walking behavior specifically, this entails more research focused on perceived walkability, but also more data collection of pedestrian environments at the micro-scale. When adding into consideration the current state of the walkability field, common walkability measures that focus primarily on objectively measured proxies at the meso-scale are likely to become less accurate in predicting walking rates and promoting improvements in a post COVID world. This is primarily a result of the lack of ability of objective walkability measurements to account for pedestrians perceptions and socio-demographic characteristics (Battista and Manaugh 2017, Blecic et al. 2016, Gebel, Bauman, and Owen 2009, Koohsari et al. 2021, Tuckel and Milczarski 2015) in conjunction with the limited representativity that meso-scale measures offers of walking environments with which pedestrians interact (Blecic et al. 2016, Brown and Jensen 2020). Both of these limitations were observed through this research as well, primarily in Chapter 2 when assessing the ability of Walkscore© to contribute to perceived walkability modelling. In addition to these previous findings, I also underscored the limitation of individual walkability indices to capture the complex nature of walking behavior. Indeed, through both Chapters 2 and 3, I highlighted how Walkscore©, while being more accurate to predict walking trips, is less useful to assessments of perceived walkability. Conversely, I also showed how the MAPS-Mini audit tool, while providing more detailed data that has been linked with differential perceptions of the built environment between social groups (Jensen et al. 2017, Clifton and Livi 2005), is less efficient when aiming to model propensity to walk. As such, I make the case that using a combination of micro-scale and meso-scale as well as objective and subjective walkability indices can help better understanding the complex experience of walking in diverse settings. A growing body of literature has been calling out inconsistent practices when assessing walkability and how most methodological choices made were rarely justified (Forsyth 2015, Shashank and Schuurman 2019). Findings from this research build on such methodological analyses by stressing the need for a shift towards a multi-scalar approach to walkability and thorough considerations of the impacts of choosing one index over another when aiming to inform policy outcomes.

An additional important improvement for walking research to make in the future is that of differentiating walking for travel (i.e. purposive walking) from walking for leisure (i.e., discursive walking) when trying to understand how trip satisfaction and perceived walkability affects walking behavior. Indeed, findings of Chapter 2 clearly indicate that there are differences in how people perceive the built environment to be suitable for walking depending on the purpose of their trip. Similar findings were also found in previous studies with leisure walking being generally more difficult to model and understand due to increases heterogeneity in personal preferences (Boarnet et al. 2011, Inoue et al. 2010, Inoue et al. 2011, Hsieh and Chuang 2021). However, given the increased prevalence of telecommuting brought by the COVID-19 pandemic, some utilitarian walking trips that were previously conducted as part of daily commute could shift to be replace by leisure walks around the home. However, such changes have been shown to be dependent on the built environment of residential areas (Victoriano-Habit and El-Geneidy 2023). To better understand how to maintain and increase numbers of walking trip and pedestrians' perceptions of their quality in a post-pandemic travel context, more research needs to be dedicated towards leisure walking in particular.

A final important contextualization that emphasizes the importance of my findings relates to the glaring social and economic inequities that COVID-19 unearthed. Indeed, the pandemic and its related social distancing and lockdown measures had a disproportionate impact on women, lower-income and racialized groups in term of travel behavior, access to active living environments and wellbeing (Berkowitz et al. 2021, Yang et al. 2021, Brough, Freedman, and Phillips 2021). As such, findings from Chapter 3 highlighting the disparities in the interactions with the built environment between social groups are timely. These findings further strengthen the need for socio-demographics to be analyzed as any other independent variables when modelling walking behavior rather than control variable and even to conduct segregated modelling when relationships between socio-demographics and walking behavior is not linear. Understanding how different socio-demographic groups interact with the built environment and what other factors influence their decision to use active transport should become a primary research goal in the fields of travel behavior and walkability if actions are to be made to correct current inequities. This is important not only for the purpose of achieving more equitable access to quality active living environments and related beneficial health outcomes, but also to create more resilient urban ecosystems to increasing disruptions from climate change.

The necessary future research areas highlighted throughout this research are dependent on the availability of the relevant data. Current walking behavior datasets are still dedicated primarily to purposive (i.e. utilitarian) walking, meaning that limited data is available for analyses on discursive (i.e. leisure) walking. Similarly, publicly conducted travel behavior surveys, such as the Montréal Origin-Destination survey, often do not include travel satisfaction or travel perceptions considerations making it difficult to analyze such dimensions. Such limitations are also present in term of socio-demographics, with the Montréal Origin-Destination survey not collecting crucial characteristics such as ethnicity, immigration status and physical (dis)ability which have been linked to walking behavior (Adkins et al. 2019, Gray, Zimmerman, and Rimmer 2012). Without the adaptation of those large travel behavior surveys to include these crucial considerations, it will remain difficult to access datasets with sample sizes large enough to allow for segregated models between socio-demographic groups which are crucial moving forward to assess differential preferences and perceptions of the built environment when walking, cycling or using public-transit. This paradigm shift is important to develop a more inclusive and equitable approach to walkability research.

CHAPTER 5 – CONCLUSION

Walkability, which is a conceptualization of the factors of the built and social environment that influence walking behaviour, has been readily linked with walking behaviour. However, despite the plurality of methods used to measure it, considerations of the subjectivity of pedestrians' interactions with the built environment remain limited (Consoli et al., 2020; Fonseca et al., 2021). Overall, this research emphasises the need to shift away from walkability as centered primarily on promoting frequency of walking for travel through objective, meso-scale indices towards walkability as a multi-scalar, inherently subjective concept that is intrinsically dependent on individuals' perceptions and socio-demographic characteristics. With Chapter 2, I highlight how perceived walkability can be understood through the micro-scale built environment and how perceptions of the walkability of a specific environment change based on trip purpose. In Chapter 3, I show how walkability indices at the micro and meso-scale interact differently with socio-demographic variables when modelling walking behavior. As a whole, I show the limitations of areal, objective walkability indices such as Walkscore© in predicting perceived walkability and walking experience as well as in promoting equity in walkability interventions. Conversely, I highlight how micro-scale walkability measures such as the MAPS-Mini can provide needed details to understand predictors of subjective walkability but remain less accurate than meso-scale ones in predicting walking behaviour.

Giving these findings, I echo calls from previous studies that the choice of walkability indices and what is considered to be walkable should be more theoretically grounded (Forsyth 2015, Shashank and Schuurman 2019) as it is heavily dependent on pedestrians' preferences and socio-demographics characteristics (Adkins et al. 2019, De Vos et al. 2022, Manaugh and El-Geneidy 2011). People have differential interactions with the built environment based on their own socio-demographic and socio-economic status as well as their own preferences. over-simplifications of the complex nature of walking behavior as the product of walkability measures, without contextualization of the individual's socio-demographic characteristics, can lead to increased inequities. Given these results, I suggest the need to derive walkability indices that combine both meso-scale and micro-scale elements, as well as objective and subjective elements. This also entail developing a better understanding of the differences in walking experience when walking for leisure as opposed to walking for travel. To that extent, subjective walkability should take a larger place in the policy making process when aiming to design more inclusive pedestrian environments. Lastly, I argue that more needs to be done to derive indices that can reflect the varying realities across socio-demographic groups to be able to address current inequities in walking behavior and walking experience. These tailored indices will be crucial to inform relevant interventions on pedestrian environments to improve the walking experience and the frequency of walking of underserved groups. For instance, a quasi-experimental approach to test the effects of interventions and policies aimed at improving walkability on different social group could present a beneficial pathway forward.

CHAPTER 6 - REFERENCES

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APPENDIX 1 – MODIFIED MAPS-MINI AUDIT TOOL – WAVE 1

Questions	Responses	Score	Source
Segment Code	Written	-	-
Street Name	Written	-	-
Cross Streets	Written	-	-
Is the segment auditable?	Yes / No	-	-
Intersection			
1. Is a pedestrian walk signal present?	No Yes at one intersection Yes at both intersection	0 1 2	MAPS Mini
1.1 What is the crossing time given to pedestrians?	# of seconds	-	Authors
2. Is there a ramp at the curb(s)?	No Yes, at least at one curb at one intersection Yes, at all curbs at one intersection Yes, at both intersections but not at all curbs Yes, at all curbs at both intersections	0 1 1 1 2	MAPS Mini
3. Is there a visible marked crosswalk?	No Yes, at one intersection Yes, at both intersection	0 1 2	MAPS Mini
3.1 What is the composition of the marked crosswalk?	Different Material / Painted / Raised	-	Authors
Land Use			
4. Residential land-use [4 categories]	Count [Buildings with separate entrances]	-	MAPS Abb.
5. Other land-uses [22 categories]	Count [Buildings with separate entrances; lots]	-	MAPS Abb.
5.16 Parks	0 1 2+	0 1 2	MAPS Mini
6. Main type of land use	Greenspace / Vacant / Industrial / Residential Commercial / Mixed	0 1	MAPS Mini
Street Amenities			
7. How many public transit stops are present?	0 1 2+	0 1 2	MAPS Mini
8. Are streetlights installed?	None Some Ample	0 1 2	MAPS Mini
9. Are there any benches or places to sit (include bus stop benches)?	No Yes	0 1	MAPS Mini
10. Presence of bicycle racks?	Count [0 – 20+]	-	Authors

Questions	Responses	Score	Source
11. Is there a designated bike path?	No Sharrow Painted line Physical barrier - Multi-use path Physical barrier – Bollard Physical barrier – Concrete / grass buffer	0 0 1 2 2 2	MAPS Mini
Aesthetic			
12. Are the buildings well maintained?	0-99% 100%	0 1	MAPS Mini
13. Is graffiti/tagging present (do not include murals)?	Yes No	0 1	MAPS Mini
14. Cleanliness – is there any litter, rubbish, broken glass, discarded items in the segment?	None or almost none. Yes, some. Yes, lots.	-	SPACES
Sidewalks			
15. Is a sidewalk present?	No Yes, on one side Yes, on both sides. Pedestrian Street	0 1 2 2	MAPS Mini
15.1 Are there poorly maintained sections of the sidewalk that constitute major trip hazards?	Any None	0 1	MAPS Mini
15.2 Is a sidewalk buffer present?	No Yes, on one side Yes, on both side	0 1 2	MAPS Mini
16. What percentage of the length of the sidewalk/walkway is covered by trees, awnings or other overhead coverage?	0-25 % / no sidewalk 26-75% 76-100%	0 1 2	MAPS Mini
Subjective scores			
17.1 On a scale of 1-10, how walkable would you rate this segment for travel?	0 – 10	-	Authors
17.2 On a scale of 1-10, how walkable would you rate this segment for leisure?	0 – 10	-	Authors

APPENDIX 2 – MODIFIED MAPS-MINI AUDIT TOOL – WAVE 2

Questions	Responses	Score	Source
Segment Code	Written	-	-
Street Name	Written	-	-
Cross Streets	Written	-	-
Is the segment auditable?	Yes / No	-	-
Intersection			
1. Is a pedestrian walk signal present?	No	0	MAPS
	Yes at one intersection	1	Mini
	Yes at both intersection	2	
2. Is there a ramp at the curb(s)?	No	0	MAPS
	Yes, at least at one curb at one intersection	1	Mini
	Yes, at all curbs at one intersection	1	
	Yes, at both intersections but not at all curbs	1	
	Yes, at all curbs at both intersections	2	
3. Is there a visible marked crosswalk?	No	0	MAPS
	Yes, at one intersection	1	Mini
	Yes, at both intersection	2	
3.1 What is the composition of the marked crosswalk?	Different Material	-	Authors
	Painted		
	Raised		
Land Use			
4. Main Residential Land-Use	No residential land use	-	Authors
	Detached single family houses		
	Attached single family houses (Row houses)		
	Multi-units / Plex (2-6 units)		
	Apartment / condo buildings (7+ units)		
	Above street retail apartments / condos		
5. Non-Residential Land-Use [Select All that are Present]	Grocery/supermarket	-	Authors
	Fast food restaurant (Multinational, national or local chains)		
	Sit-down restaurant / Coffee shop		
	Office building.		
	Pharmacy / Drugstore		
	Health-related professional (e.g., chiropractor, Dr. office)		
	School, daycare, or higher education building		
	Place of worship (e.g., church, synagogue, convent, mosque, etc.)		
	Municipal services (e.g., library, police station, city hall, etc.)		
	Governmental building		
	Bank or credit union		

Questions	Responses	Score	Source
	Hotel Indoor fitness area (e.g., commercial gyms, dance studio, martial arts studio...) General entertainment (e.g., movie theatre, arcade) Night entertainment (bars, night clubs) Other service (e.g., salon, lawyer, accountant, laundry/dry cleaner…) Other retail (e.g., books, clothing, hardware...) Car dealership Industrial lots / Factory Parking lot Underground Parking entrance Empty commercial spaces Empty lots None		
6. Parks	0 1 2+	0 1 2	MAPS Mini
7. Main type of land use	Industrial & Vacant Green space (parks, accessible forest) Residential Institutional (Education, governmental) Commercial Mixed	0 0 0 1 1 1	MAPS Mini
Street Amenities			
8. Are streetlights installed?	None Some Ample	0 1 2	MAPS Mini
9. Are there any benches or places to sit?	No Yes, but only bus stops Yes	0 1 1	MAPS Mini
10. Is there a designated bike path?	No Sharrow Painted line Physical barrier - Multi-use path Physical barrier – Bollard Physical barrier – Concrete / grass buffer	0 0 1 2 2 2	MAPS Mini
Aesthetic			
11. Are the buildings well maintained?	0-49% 50-99% 100%	0 0 1	MAPS Mini
12. Is graffiti/tagging present (do not include murals)?	Yes No	0 1	MAPS Mini
Sidewalks			

Questions	Responses	Score	Source
13. Is a sidewalk present?	No Yes, on one side Yes, on both sides. Pedestrian Street	0 1 2 2	MAPS Mini
13.1 Are there poorly maintained sections of the sidewalk that constitute major trip hazards?	A lot (More than 25% of sidewalk) Some (Less than 25% of sidewalk) None	0 0 1	MAPS Mini
13.2 Is a sidewalk buffer present?	No Yes, on one side Yes, on both side	0 1 2	MAPS Mini
14. What percentage of the length of the sidewalk/walkway is covered by trees, awnings or other overhead coverage?	0-25 % 26-75% 76-100%	0 1 2	MAPS Mini
Subjective scores			
15. What are your perception of the following elements of the segment: (Table: Low-Medium-High)	Level of Noise Presence of litter, rubbish Air pollution Motorized Traffic Density	-	Authors
16.1 On a scale of 1-10, how walkable would you rate this segment for travel?	0 – 10	-	Authors
16.2 On a scale of 1-10, how walkable would you rate this segment for leisure?	0 – 10	-	Authors
17. Please provide a short justification of your score	[Written]	-	Authors