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Do differences in built environments explain age differences in transport walking across neighbourhoods?

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ABSTRACT

Background: The neighbourhood built environment (BE) provides opportunities for regular walking for transport (WfT). Within the same city, age differences in WfT can vary significantly across neighbourhoods, although little is known about the reasons for this variation. This cross-sectional study investigated the contribution of the BE to explaining age differences in WfT across neighbourhoods.
Methods: This investigation used baseline (2007) data from the How Areas in Brisbane Influence HealTh and AcTivity (HABITAT) Study. The sample included 11,035 residents aged 40–65 years living in 200 neighbourhoods in Brisbane, Australia (68.4% response rate). Self-reported weekly minutes of WfT were categorized into none (0 mins) and any (1–840 mins); age was categorized into 40–48, 49–57 and 58–65 years. Objectively assessed neighbourhood-level measures of the BE included residential density, street connectivity and land-use mix. Analyses involved multilevel binomial logistic regression with age as main predictor, adjusting for gender, socioeconomic position, residential self-selection, and neighbourhood disadvantage.
Results: On average, older adults were significantly less likely to walk for transport. Age differences in WfT seemed to vary significantly across neighbourhoods, and the magnitude of the variation for older groups was twice that of their younger counterparts. The environmental measures analysed played a relatively limited role in explaining neighbourhood differences in the age-WfT relationship. Residential density and street connectivity explained up to 13% and 9% respectively of the observed between-neighbourhood variation in WfT across age groups.
Conclusion: Neighbourhood-level factors semeed to influenced the WfT of younger and older adults differently, with older adults being more sensitive to their neighbourhood environment. In Brisbane, age differences in WfT were smaller in areas with higher residential density and street connectivity. These results favor the ongoing investigation of demographic heterogeneity around neighbourhood averages in other urban contexts to inform tailored ecological interventions that facilitate WfT for all age groups everywhere, supporting active aging communities.

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1. Introduction

Age is a consistent predictor of physical activity (PA), with older adults being less active than their younger counterparts (Bauman et al., 2012). Walking is the most common and preferred form of PA among older adults (Satariano et al., 2012; Touvier et al., 2010), whereas young adults are more likely to participate in vigorous-intensity PA (Hallal et al., 2012). Regular walking contributes to daily energy expenditure (Morris and Hardman, 1997), reducing or postponing morbidity and mortality from non-communicable diseases (Fortes et al., 2013; Murtagh et al., 2015).

Walking for transport (WfT) is undertaken with the purpose of reaching a destination such as work, the shops or public transit (National Heart Foundation of Australia, 2014). As an alternative to vehicular transportation, walking has synergistic co-benefits across several portfolios (health, transport, community and environment) (Ewing and Cervero, 2010), and contributes to overall PA levels in populations, particularly in older adults (Cerin et al., 2017). Seniors are likely to experience greater benefits from shifting to WfT than their younger counterparts, since it facilitates their independent living by enabling access to commercial and health services, as well as community life and opportunities for social interaction (Levasseur et al., 2017), which might translate into better health (Mueller et al., 2015). The design of neighbourhoods can potentially reduce age disparities in overall PA participation through the incorporation of incidental WfT into daily routines, which has implications for health equity and social justice (Panter and Jones, 2010).

Active transportation is a component of active aging, acknowledged within the socio-ecological perspective underpinning the World Health Organization's *Global age-friendly cities (*World Health Organization, 2007*)*. This framework highlights the dynamic interactions between individuals and the environment in which they live, and calls for research-based evidence to inform the necessary environmental modifications that ensures elder-friendly communities which are likely to extend the health and quality of life in older age (World Health Organization, 2007; Sun et al., 2013; Plouffe and Kalache, 2010). This includes the identification of the key design elements of neighbourhoods that might delay age-related declines in WfT (Turrell et al., 2014).

The built environment comprises the neighbourhood's physical features, such as pedestrian infrastructure and street lighting, and has stronger associations with WfT compared with other types of PA, including recreational walking (McCormack and Shiell, 2011). In particular, greater residential density, street connectivity and land-use mix (common features of pedestrian-friendly neighbourhoods) are consistently associated with WfT in adults (McCormack and Shiell, 2011) and seniors (Cerin et al., 2017; Kamruzzaman et al., 2016). Higher residential density also facilitates the mixed use of land (which provides a range of destinations to walk to) as well as access to public transport, while greater street connectivity facilitates transport walking by providing direct routes to destinations (Wilson et al., 2012).

Previous multilevel research observed that WfT varies with age, with older adults less likely to walk for transport than their younger counterparts (Turrell et al., 2014; Turrell et al., 2013), possibly reflecting changes in occupational status such as retirement (Bjornsdottir et al., 2012). This evidence suggests that this is a critical life-stage for promoting transport walking (Touvier et al., 2010), particularly since shopping seems to be the most common reason for older adults leaving their homes (Davis et al., 2011). Further evidence is required to improve current understanding of the relationship between built environments and WfT among older adults (Van Cauwenberg et al., 2011).

To date, most neighbourhood-based studies have presented the overall (average) association between age and WfT (Cerin et al., 2017), overlooking the possibility that this relationship differs depending on the characteristics of neighbourhood environments. However, a previous investigation revealed that the effect of age on WfT varied significantly across neighbourhoods (Ghani et al., 2016), suggesting that the overall relationship was not necessarily reflective of the association within any particular neighbourhood. Moreover, the overall effect was potentially obfuscating important information about how neighbourhoods differentially influence the WfT of younger and older adults.

A few studies have explored age as a moderator of the relationship between the built environment and WfT (Shigematsu et al., 2009; Cerin et al., 2014; Van Cauwenberg et al., 2012), with two investigations revealing that neighbourhoods with greater land-use mix may delay the decline in WfT across time (Shigematsu et al., 2009; Cerin et al., 2014). These results suggest that a supportive built environment might be required to encourage older adults to walk more for transport. While physical function declines with age (Yen et al., 2009) and living spaces appear to shrink in older age (Laatikainen et al., 2016), pedestrian-friendly neighbourhoods may generate smaller age differences in WfT, since such features are conducive to walking for all age groups. In contrast, unfavorable environments for WfT (with less residential density, fewer street intersections and low land-use mix) may produce larger age disparities in WfT, accelerating the decline of the physical and cognitive functions in older adults as a result of walking less for transport. Therefore, the impact of the neighbourhood built environment on a person's probability of WfT might depend on their age.

Furthermore, between-neighbourhood variation of age differences in WfT might be attributed to age-specific sensitivity to environmental characteristics, reflecting the fact that younger and older adults might experience –and engage with– their local environments in distinct ways (Kavanagh et al., 2006). Thus, it is plausible that the built environment of a neighbourhood might have a stronger influence on the transport walking of older adults compared to their younger counterparts, due to the increasing multiple physical and social limitations associated with aging (Cerin et al., 2014; Inoue et al., 2011).

Consistent with the principles of social-ecological models, which posit dynamic interrelations across multiple levels of influence (Sallis et al., 2008), this study investigates the contribution of three commonly reported built environment measures (i.e. residential density, street connectivity and land-use mix) to explaining: (1) neighbourhood differences in the age-WfT relationship; and (2) between-neighbourhood variation in WfT for different age groups. The first question examines whether the effect of age on WfT varied significantly across neighbourhoods, suggesting that the overall relationship is not necessarily reflective of the association within any particular neighbourhood. The second question examines whether age differences in WfT might be moderated by the built environment (a relationship that varies only between-neighbourhoods).

2. Methods

2.1. Study design and data collection

This investigation used data from the first wave (collected in 2007) of the How Areas in Brisbane Influence HealTh and AcTivity (HABITAT) multilevel study of mid-age adults living in Brisbane(Australia). HABITAT is underpinned by a social-ecological framework, which facilitates the investigation of the relative contributions of environmental, social, psychological and socio-demographic factors on PA patterns. Details of HABITAT's sampling design have been published elsewhere (Burton et al., 2009). Briefly, a multistage probability sampling design was used to select a stratified random sample (n = 200) of Census Collection Districts (CCDs), or 'neighbourhoods', with a random sample of people aged 40–65 years from each CCD subsequently selected (85 persons on average). These neighbourhoods varied in area size (mean 878,659 m^2 with a standard error 387,408 m^2, ranging from 19,970 m^2 to 70,673,182 m^2) and topology. Eligible participants were mailed a survey between May and July of 2007 using a method developed by Dillman (2000). Of the 16,127 in-scope participants, 11,035 valid responses (68.4%) were received in 2007. The baseline sample was broadly representative of the Brisbane population (Turrell et al., 2010). The HABITAT Study received ethical clearance from the Queensland University of Technology Human Research Ethics Committee (Ref. No. 3967H & 1300000161).

2.2. Measures

2.2.1. Outcome variable

Walking for transport (WfT): a single question asked participants to report the total time (converted to minutes) spent WfT (i.e. travelling to and from work, to do errands, or to go from place to place) in the previous week. Respondents were instructed to exclude any time spent walking for exercise or recreation when answering this question.

The WfT variable was positively-skewed and included outlier values, which were top-coded to 840 min as recommended (Australian Institute of Health and Welfare, 2003), equivalent to a maximum of two hours of daily walking. As in an earlier HABITAT Study (Turrell et al., 2014), exploratory analysis of WfT revealed two relatively discrete groups: one reporting 0 mins of WfT in the previous week (representing 65% of the sample), and another reporting 1–840 min. Previous research noted that even small amounts of WfT, (which supports the use of a 1–840 min category) might contribute to meeting the recommended levels of PA (Besser and Dannenberg, 2005), currently endorsing at least 150 min of moderate intensity PA per week (World Health Organization, 2010).

2.2.2. Independent variable

Participants reported their date of birth, from which a year of age in 2007 was derived and subsequently coded into three categories: 40–48 years; 49–57 years and 58–65 years. These categories were chosen to explore how particular pre-retirement age subgroups in Australia (Deparment of Human Services, 2017) differed in their WfT. Furthermore, the 65 years cut off also corresponds with the Australian physical activity guidelines for adults aged 65 years and over Common Wealth Department of Health, 2014.

2.2.3. Measures of the neighbourhood built environment

The selection of built environment measures was based on previous multilevel research which has identified residential density, street connectivity and land-use mix as important for WfT among older adults (Cerin et al., 2017; Kamruzzaman et al., 2016; Van Cauwenberg et al., 2013). The three built environment measures examined in this investigation were derived from supplied by the Brisbane City Council (the local government responsible for the geographical area covered by the HABITAT Study) and MapInfo StreetPro computer program (2016).

As recommended to ensure comparability between studies (Lamb and White, 2015; Barnett et al., 2017), continuous spatial measures of the built environment were developed for each of the 200 HABITAT neighbourhoods for overlaying on survey responses (McCormack and Shiell, 2011) using ArcMap (Arcgis Desktop computer program, 2011). Table 1 provides further details on the built environment measures used in the analyses.

An exploration of Brisbane neighbourhoods (Fig. 1) revealed that the built environment measures were positively-skewed and distributed over a relatively wide range (where 0 represents the lowest residential density, street connectivity and land-use mix), particularly for street connectivity and land-use mix.

2.2.4. Covariates

Gender: participants reported their gender as either male or female.

Education: respondents provided the highest educational qualification attained, which was coded as follows: (1) bachelor degree or higher (including postgraduate diploma, master's degree, or doctorate), (2) diploma (associate or undergraduate), (3) vocational (trade or business certificate or apprenticeship), and (4) no post-school qualifications.

Occupation: respondents provided their job title, which was classified according to the Australian and New Zealand Standard Classification of Occupations (ANZSCO) (Australian Bureau of Statistics, 2013) and recoded into five categories: (1) managers/ professionals (managers and administrators, professionals and paraprofessionals); (2) white-collar employees (clerks, salespersons and personal service workers); (3) blue-collar employees (tradespersons, plant and machine operators and drivers and other laborers

Table 1
Built environment measures.

Measure	Definition	Formula	Unit of measurement	Summary post-transformation	Source of the data
Residential density	Measured by calculating the number of dwellings per hectare of residential land within the CCD in which the participant resided at the time of data collection	Sum of number of dwellings / Sum of the shape area in m^2 / 10,000	For ease of interpretability, residential density was divided by 5, such that the coefficient could be interpreted as the likelihood of WfT for a 5 dwelling increase.	Range 0.04–28.85, mean 3.87 (SD 3.05)	Brisbane City Council Land Use Activity Database (LUAD)
Street connectivity	Measured through a count of the number of four-way or more intersections within each of the CCDs	Count of four or more street intersections.	The number of four-way or more intersections.	Range 0–12, mean 2.5 (SD 2.3)	Pitney Bowes StreetPro (2007).
Land-use mix	Derived as the balance of five land-use codes (retail, office, social service, recreation and residential) that quantified the proportion of land area within a CCD, using an entropy equation described previously (Leslie et al., 2007). This entropy score ranged from 0 to 1, with 0 representing complete homogeneity of land use within the CCD, and 1 indicating an even distribution of the five types of land-use.	$-\frac{\sum_k (p_k \ln p_k)}{\ln N}$ (Leslie et al., 2007)	For ease of interpretability, the land-use mix variable was multiplied by 10, so that the coefficient could be interpreted as a 10% increase in land-use mix.	Entropy scores range 0.91–7.96, mean 3.46 (SD 1.49)	Brisbane City Council Cadastre

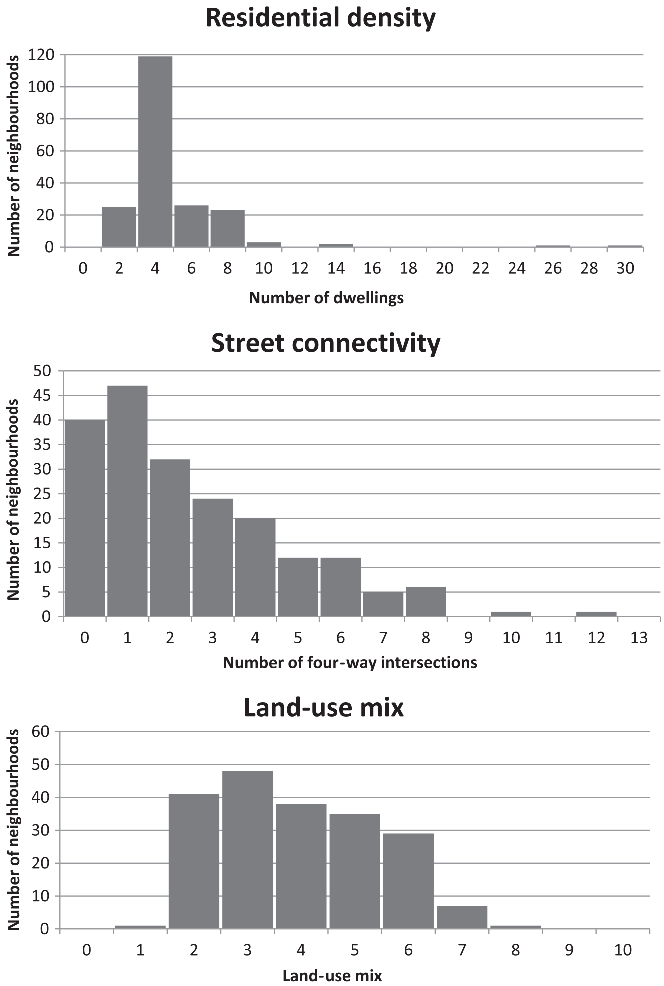

Fig. 1. Distribution of built environment exposures across the 200 HABITAT neighbourhoods.

and related workers); (4) not in the workforce (home duties and retired); and (5) not easily classifiable (not employed, students, permanently unable to work or other category).

Household income: respondents provided an estimate of the total pre-tax annual household income through a question comprising 13 income categories. For analysis, these were re-coded into the following six categories: (1) > AU$130,000, (2) AU $129,999–72,800; (3) AU$72,799–52,000; (4) AU$51,999 – 26,000; (5) < AU$25,999; and (6) not classified (including blank responses, 'Don't know' or 'Don't want to answer').

Residential self-selection: to assess residential attitudes, participants were asked to respond to five Likert-type items in 2007, ranging from 'not at all important' to 'very important' on a number of statements regarding 'How important were the following reasons for choosing your current address?'. Principal components analysis (PCA) with Varimax rotation identified three factors composed of items relevant for controlling for WfT self-selection with loadings of 0.50 or above, as recommended (Matsunaga, 2015). These were subsequently described as follows:

- 'destinations' (three items: ease of walking to places; closeness to public transport; and wanted to live close to shops, Cronbach's alpha = 0.80);
- 'nature' (three items: near to green-space or bushland; closeness to open space (e.g. parks); and closeness to recreational facilities, Cronbach's alpha = 0.78); and
- 'family' (two items: closeness to schools; and closeness to childcare, Cronbach's alpha = 0.62).

Neighbourhood-level disadvantage: each of the 200 neighbourhoods was assigned a socioeconomic score using the Australian Bureau of Statistics' Index of Relative Socioeconomic Disadvantage (IRSD) (Australian Bureau of Statistics, 2011). The Index reflects each area's overall level of disadvantage based on 17 socioeconomic attributes, including education, occupation, income, unemployment, and household tenure. The derived socioeconomic scores from the HABITAT neighbourhoods were then quantised as percentiles, relative to all of Brisbane (Burton et al., 2009) ranging from 1–100 (with a mean of 57.2 and SD 28.1), with lower scores

Table 2
Socio-demographic characteristics of the analytic sample by age group and minutes of transport walked: 2007 HABITAT data.

	40–48 years		49–57 years		58–65 years	
Total (N)	**0 mins 2,598**	**1–840 mins 1,580**	**0 mins 2,463**	**1–840 mins 1,288**	**0 mins 1,667**	**1–840 mins 754**
	%	%	%	%	%	%
Gender						
Men	61.3	38.7	64.0	36.0	68.6	31.4
Women	63.0	37.0	66.9	33.1	69.1	30.9
Education						
Bachelor degree or higher	53.6	46.4	57.8	42.2	60.1	39.9
Diploma/associate degree	63.6	36.4	61.2	38.8	67.7	32.3
Certificate	67.3	32.7	69.9	30.1	72.0	28.0
No post-school qualification	67.9	32.1	72.0	28.0	72.2	27.8
Occupation						
Professional	59.3	40.7	62.8	37.2	66.0	34.0
White collar	61.6	38.4	64.3	35.7	69.6	30.4
Blue collar	71.4	28.6	74.9	25.1	76.3	23.7
Not in workforce	62.1	37.9	68.7	31.3	69.5	30.5
Not easily classifiable	60.2	39.8	61.9	38.1	62.7	37.3
Income						
$130,000+	62.3	37.7	65.6	34.4	70.2	29.8
$72,800-129,999	61.7	38.3	65.2	34.8	64.9	35.1
$52,000–72,799	58.6	41.4	64.7	35.3	69.7	30.3
$26,000–51,999	63.1	36.9	66.0	34.0	69.8	30.2
Less than $25,999	57.8	42.2	60.2	39.8	66.4	33.6
Not classified	68.6	31.4	70.2	29.8	72.8	27.2

denoting more disadvantaged neighbourhoods.

2.3. Statistical analyses

Of the 11,035 participants who returned a valid questionnaire in 2007, the following were excluded from the analyses: 47 had incomplete data for education, 178 had incomplete data for the outcome variable (WfT), and 460 had incomplete data for the residential self-selection variables, giving a total of 684 missing records (6.2% of the eligible participants). Sensitivity analyses revealed that participants who were blue collar ($p = 0.001$), not classified for occupation ($p = 0.000$) and not classified for income ($p = 0.013$) were significantly more likely to be in the missing group of 684.

A listwise deletion (rather than multiple imputation) was applied to the 684 missing records based on the following rationale: the missing data approached the recommended 5% threshold for imputation (Tabachnick and Fidell, 2007); the original sample was broadly representative of the targeted population (Turrell et al., 2010); the efficiency gains offered by applying missing data methods (which add another layer of measurement error to the data) are often minor in large samples (Cheema, 2014); and the analytic sample remained large enough to address the study objectives.

The final analytical sample comprised 10,350 participants nested within 200 neighbourhoods, and the demographic characteristics are presented in Table 2. The number of respondents per neighbourhood ranged from 11 to 151, with an average of 52 respondents (95% CI 48.0–55.5).

2.3.1. Modelling strategy

Age was the independent variable of interest, and reference categories for analyses were non-walkers and the youngest age group (40–48 years). Data were prepared in Stata v.14.1 (Stata Statistical Software, 2016) and analysed in ***MLwiN*** v.2.36 (MLwiN Version 2.36 computer program, 2016). WfT was analysed as a binomial dependent variable using multilevel logistic regression through two-level random intercept Markov chain Monte Carlo (MCMC) binomial logit models (first-order marginal quasi-likelihood base estimates; burn-in = 500, chain = 50,000).

The modelling approach corresponded with the aims of the study. The *average neighbourhood effects* of age differences in WfT were estimated first (adjusting for gender) as shown in Eq. (1), and results are reported as odds ratios (ORs) with 95% Credible Intervals (CrIs).

$$\mathrm{WfT_{ij}} = \beta_{0j} + \beta_1 \mathrm{age_{ij}} + \beta_2 \mathrm{gender_{ij}} + e_{ij} + u_{0j} \quad (1)$$

Equation subscripts:

WfT_{ij} = walking category for resident **i** in neighbourhood **j**
β_{0j} = overall intercept (grand mean)

β_{1j} = overall slope coefficient for age (average change across all neighbourhoods)
β_{2j} = overall slope coefficient for gender (average change across all neighbourhoods)
e_{ij} = level-1 random effect (within-neighbourhood variation)
u_{0j} = level-2 random effect of the intercept (between-neighbourhood variation)
u_{ij} = level-2 random effect of the slope for age (variation in the effect of age on WfT across neighbourhoods)

A *random coefficient* was introduced for each age group, which enabled the average neighbourhood effects of age on the likelihood of WfT to vary across neighbourhoods. This analysis produced a neighbourhood-level random effect u_{1j} (also referred to as between-neighbourhood variation in the effect of age on WfT), bolded in Eq. (2).

$$\mathrm{WfT_{ij}} = \beta_{0j} + \boldsymbol{\beta_1 \mathrm{age_{ij}}} + \beta_2\mathrm{gender_{ij}} + \mathrm{e_{ij}} + \mathbf{u_{1j}} \tag{2}$$

Further adjustment for education, occupation, household income, residential self-selection and neighbourhood disadvantage produced baseline estimates. A joint Wald test was then conducted to examine whether the effect of age on WfT varied significantly across neighbourhoods, through assessing the null hypothesis of no between-neighbourhood variation in the likelihood of WfT for the random coefficient ($H_0 : \sigma_{u01} = \quad \sigma^2_{u1} = 0$) MLwiN Version 2.36 computer program (2016).

The *neighbourhood-level variance functions* from the fully adjusted baseline model estimated the magnitude of between-neighbourhood variation in the probability of engaging in WfT for each age group (Goldstein, 2011). These neighbourhood-level variance functions (which provide an indication of the age sensitivity to the neighbourhood environment in regards to WfT), were calculated using Eq. (3) (where age = x):

$$var(u_{0j} + u_{1j}x_{1ij}) = \sigma^2_{u0} + 2\sigma_{u01}x_{ij} + \sigma^2_{u1}x^2_{ij}. \tag{3}$$

The neighbourhood-level variance for adults aged 40–48 years (the reference group; x = 0) in the likelihood of WfT was calculated using Eq. (4).

$$var(u_{0j} + u_{1j}x_{1ij}) = var(u_{0j}) = \sigma^2_{u0}. \tag{4}$$

The neighbourhood-level variance for adults aged 49–57 years (comparison group 1; x = 1) in the likelihood of WfT was calculated using Eq. (5).

$$var(u_{0j} + u_{1j}x_{1ij}) = var(u_{0j} + \mathrm{u_{1j}}) = \sigma^2_{u0} + 2\sigma_{u01} + \sigma^2_{u1}. \tag{5}$$

The neighbourhood-level variance for adults aged 58–65 years (comparison group 2; x = 2) in the likelihood of WfT was calculated using Eq. (6).

$$var(u_{0j} + u_{1j}x_{1ij}) = var(u_{0j} + \mathrm{u_{1j}}) = \sigma^2_{u0} + 2\sigma_{u12} + \sigma^2_{u2}. \tag{6}$$

To assess whether differences in built environments (i.e. residential density, street connectivity and land-use mix) explain neighbourhood differences in the age-WfT relationship (i.e. whether they moderate the variation across neighbourhoods in this relationship), we followed the *Best-practice recommendations for estimating cross-level interaction effects* (Aguinis et al., 2013), by incorporating a *cross-level interaction* between age at the individual-level, and each of the built environment measures considered at the neighbourhood-level. We then assessed reductions from the fully adjusted baseline model in the random coefficients for age (Snijders and Bosker, 1999).

Finally, to investigate whether differences in built environments explain the between-neighbourhood variation in WfT for younger and older adults, we incorporated each of the built environment measures into the fully adjusted baseline model as fixed-effects and assessed reductions in neighbourhood-level variance functions in the likelihood of WfT for each age group.

3. Results

3.1. The relationship between age and transport walking

The average association between age and WfT revealed that older age groups were less likely to walk for transport, and this was a graded association (Fig. 2): 16% lower (OR 0.84, 95% CrI 0.77–0.93) for those aged 49–57 years; and 27% lower (OR 0.73, 95% CrI 0.65–0.82) for those aged 58–65 years, compared to the youngest age group (40–48 years).

Table 3 presents the results of the analytic steps addressing the aims of this study. The relationship between age and WfT remained statistically significant after adjustment for additional covariates, including socio-economic position, residential self-selection and neighbourhood disadvantage (Model 1 in Table 3; 0.82, 95% CrI 0.73–0.92 for those aged 49–57 years and 0.72, 95% CrI 0.63–0.83 for those aged 58–65 years).

3.2. Variation of the average age differences in transport walking across neighbourhoods

The Wald Test (Model 1) indicated that the relationship between age and WfT varied significantly across neighbourhoods for the 49–57 and 58–65 year olds, compared with those aged 40–48 years (p = 0.006). These results suggest that the average relationship between age and WfT differed depending on the characteristics of the neighbourhood environments within which individuals resided.

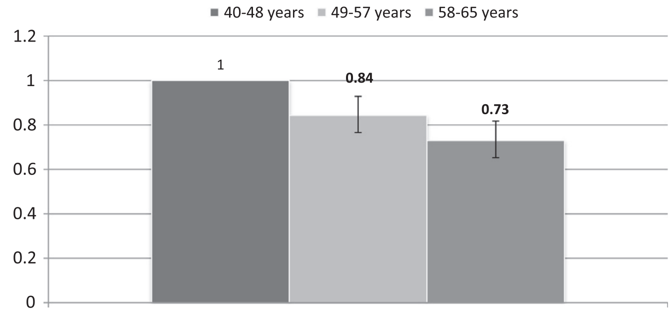

Fig. 2. Age differences in transport walking in 2007 (average across the 200 HABITAT neighbourhoods)†. †Model 1: age differences in the odds of WfT with 95% credible intervals, adjusted for gender.

Table 3
Age differences in transport walking, variation of this relationship across neighbourhoods, and the contribution of the built environment to explaining this variation.

	Baseline		**Residential density**				**Street connectivity**				**Land-use mix**			
	M1		M2		M3		M4		M5		M6		M7	
Fixed effects [a]	OR	95% CrI	OR	95% CrI	OR	95% CrI	OR	95% CrI	OR	95% CrI	OR	95% CrI	OR	95% CrI
40–48 years	1.00	–	1.00	–	1.00	–	1.00	–	1.00	–	1.00	–	1.00	–
49–57 years	**0.82**	**0.73,0.92**	**0.82**	**0.73,0.91**	**0.72**	**0.60,0.86**	**0.82**	**0.73,0.92**	**0.75**	**0.64,0.88**	**0.82**	**0.73,0.92**	**0.67**	**0.50,0.91**
58–65 years	**0.72**	**0.63,0.83**	**0.72**	**0.63,0.82**	**0.59**	**0.49,0.72**	**0.73**	**0.64,0.83**	**0.69**	**0.57,0.82**	**0.72**	**0.63,0.83**	**0.63**	**0.45,0.90**
L2 exposure [b]	–	–	**1.05**	**1.02,1.08**	1.02	0.99,1.06	**1.05**	**1.02,1.09**	**1.04**	**1.00,1.08**	1.00	0.95,1.05	0.98	0.92,1.04
Interactions														
40–48	–	–	–	–	1	–	–	–	1	–	–	–	1	–
L2*49–57	–	–	–	–	**1.04**	**1.00,1.08**	–	–	1.04	0.99,1.09	–	–	1.06	0.98,1.14
L2*58–65	–	–	–	–	**1.06**	**1.01,1.10**	–	–	1.02	0.97,1.08	–	–	1.04	0.95,1.13
Random effects														
Random coefficients (s.e.) [c]														
40–48 years	–		–		–		–		–		–		–	
49–57 years	**0.113 (0.038)**		**0.110 (0.039)**		**0.108 (0.036)**		**0.117 (0.041)**		**0.109 (0.039)**		**0.112 (0.039)**		**0.111 (0.037)**	
58–65 years	**0.114 (0.041)**		**0.112 (0.042)**		**0.109 (0.040)**		**0.114 (0.043)**		**0.115 (0.043)**		**0.113 (0.044)**		**0.116 (0.042)**	
P-value	**0.006**		**0.009**		**0.007**		**0.007**		**0.012**		**0.010**		**0.006**	
Variance functions (s.e.) [d]														
40–48 years	**0.132 (0.034)**		**0.130 (0.035)**		**0.130 (0.035)**		**0.125 (0.034)**		**0.124 (0.034)**		**0.135 (0.035)**		**0.133 (0.034)**	
49–57 years	**0.271 (0.051)**		**0.245 (0.046)**		**0.247 (0.048)**		**0.248 (0.047)**		**0.245 (0.047)**		**0.274 (0.051)**		**0.273 (0.051)**	
58–65 years	**0.261 (0.055)**		**0.226 (0.048)**		**0.229 (0.049)**		**0.244 (0.051)**		**0.248 (0.053)**		**0.262 (0.056)**		**0.264 (0.055)**	

Note: Boldface indicates significance. Model 1: age differences in WfT (randomized at the neighbourhood level), adjusted for gender, socioeconomic position (education, occupation and household income), residential self-selection and neighbourhood disadvantage.
Models 2, 4 and 6 = M1 + each of the built environment measures entered into the models separately
Models 3, 5 and 7 = M2, M4 & M6 + cross-level interactions of age with each of the built environment measures

[a] Fixed effects capturing the neighbourhood average (pooled) effects of age differences in the likelihood of WfT.

[b] L2 exposure: main effects for each level 2 environmental exposure i.e., residential density in M2 and M3, street connectivity in M4 and M5, and land use mix in M6 and M7.

[c] Random coefficients (with standard error) testing whether the age differences in the likelihood of WfT are the same everywhere (reflecting the average effect) or whether the relationships vary across neighbourhoods (thus, the neighbourhood-level variance functions are reported in grey).

[d] Variance functions capturing the extent of between-neighbourhood variation in WfT for each age group (thus, the random coefficients are reported in grey).

3.3. Between-neighbourhood variation in the probability of transport walking for each age group

The neighbourhood-level variance functions in the baseline model (Model 1) revealed significant between-neighbourhood variation in the likelihood of WfT for each age group, although the magnitude of the variation for the two older groups (0.271 and 0.261 respectively) was twice that of the youngest group (0.132). These results suggest that older adults might be more sensitive to their neighbourhood environments in regards to WfT.

3.4. The contribution of the built environment to explaining neighbourhood differences in the age and walking for transport relationship

There were significant cross-level interactions between the older age groups and residential density (Model 3), indicating that each age-groups' propensity to walk for transport was differently influenced by the level of density in the neighbourhood environment. The addition of the cross-level interaction reduced the random coefficients by 4.4% for both the 49–57 and 58–65 year olds, suggesting that residential density explained a small part of the neighbourhood differences in the relationship between age and WfT.

The cross-level interaction between age and street connectivity (Model 5) did not approach significance. The addition of the cross-level interaction reduced the random coefficient by 3.5% for the 49–57 year olds only.

Likewise, the cross-level interaction between age and land-use mix (Model 7) did not approach significance. The addition of the cross-level interaction reduced the random coefficient by 1.8% for the 49–57 year olds only.

3.5. The contribution of the built environment to explaining between-neighbourhood variation in walking for transport for each age group

There was a significant relationship between residential density and WfT (Model 2); residents living in denser neighbourhoods were more likely to report waking for transport in the previous week. The inclusion of residential density as a fixed effect accounted for a small proportion of the between-neighbourhood variation in WfT for each of the age groups: 1.5%, 9.6%, and 13.4% for those aged 40–48, 49–57, and 58–65 years respectively.

Likewise, there was a significant relationship between street connectivity and WfT (Model 4); residents living in more connected neighbourhoods were more likely to report waking for transport in the previous week. The inclusion of street connectivity as a fixed effect accounted for a small proportion of the between-neighbourhood variation in WfT for each of the age groups: 5.3%, 8.5%, and 6.5% for those aged 40–48, 49–57, and 58–65 respectively.

The relationship between land-use mix and WfT (Model 6) did not approach significance. The inclusion of land-use mix as a fixed effect did not explain the between-neighbourhood variation in WfT for any of the age groups.

4. Discussion

Within the same capital city, age differences in WfT might vary significantly across neighbourhoods (Ghani et al., 2016), although the reasons for this variation remain unknown. Since the built environment of neighbourhoods might influence (encourage or discourage) the transport walking of older adults differently than their younger counterparts (Shigematsu et al., 2009; Cerin et al., 2014), this study investigated the contribution of the built environment to explaining age differences in WfT across neighbourhoods.

As expected based on previous research (Turrell et al., 2014; Turrell et al., 2013; Ghani et al., 2016; Doescher et al., 2014; Shimura et al., 2012; Van Dyck et al., 2012), older adults were less likely to walk for transport than their younger counterparts. The time around retirement has been identified as a critical life-stage for promoting active aging through walking (Livingstone et al., 2003). Previous longitudinal studies observed post-retirement decreases in WfT (Turrell et al., 2014; Sprod et al., 2017), as well as increases in time spent watching television (Sprod et al., 2017), indicating that WfT in pre-retirement is not being replaced with WfT in other contexts (e.g. walking to the shops) in post-retirement (Sprod et al., 2017). This evidence suggests a contextual opportunity for ecological interventions around retirement age that facilitates incidental WfT.

Consistent with a previous study (Ghani et al., 2016), age differences in WfT seemed to significantly across neighbourhoods within Brisbane, suggesting that while some neighbourhood environments might influence younger and older adults similarly, other environments might have a differential impact on WfT. Furthermore, variation in WfT was observed between neighbourhoods for each age group, although the magnitude of the variation for older adults was twice that of their younger counterparts. These results suggest that the neighbourhood environment differentially shapes and circumscribes the transport walking of younger and older adults, with older adults being more sensitive to environmental factors. These findings are consistent with emerging evidence across geographical settings, noting that the built environment might be more relevant for older adults in regards to WfT (Cerin et al., 2017, 2014; Inoue et al., 2011), as they might be more susceptible to physical barriers because of functional limitations (Cerin et al., 2014; Inoue et al., 2011). Older adults also spend more time in their neighbourhood, compared to their younger counterparts (Laatikainen et al., 2016), which suggests an opportunity for built environment interventions that facilitate active aging in place, and reduce the age disparity in overall PA participation through increases in WfT.

In this study, we investigated the contribution of the built environment (objectively measured using residential density, street connectivity and land-use mix) to explaining: (1) neighbourhood differences in the age-WfT relationship; and (2) between-neighbourhood variation in WfT for different age groups.

First, consistent with previous literature (Cerin et al., 2017; McCormack and Shiell, 2011; Kamruzzaman et al., 2016), higher residential density and street connectivity were significantly associated with the likelihood of WfT in our sample, although land-use mix was not. However, only residential density moderated the relationship between age and WfT, with older groups being more affected by residential density in their likelihood of WfT. Therefore, higher residential density might be required to encourage older adults to walk for transport, a finding consistent with emerging research noting age as a potential moderator influencing the strength of the relationship between the environment and WfT (Shigematsu et al., 2009; Cerin et al., 2014; Van Cauwenberg et al., 2012). The cross-level interaction models of age with each of the built environment measures marginally reduced the baseline random coefficients, suggesting that the built environment played a relatively limited role in explaining neighbourhood differences in the age-WfT relationship. Likewise, no consistent moderating effects of age were reported by a recent systematic review and meta-analysis of the environmental correlates of total walking in older adults (Barnett et al., 2017).

Second, the present study investigated whether –and to what extent–three common measures of the neighbourhood built environment explained between-neighbourhood variation in WfT for younger and older adults. As hypothesised, residential density and street connectivity partially explained the between-neighbourhood variation in WfT for each age group, particularly for older adults. This is consistent with a recent review and meta-analysis of active travel in older adults, noting that self-reported WfT was positively associated with both objective and perceived residential density and street connectivity (Cerin et al., 2017). Contrary to our hypothesis (and the above mentioned meta-analysis, which noted that WfT was positively associated with objective and perceived land-use mix (Cerin et al., 2017)), objective land-use mix in our study did not noticeably attenuate the observed between-neighbourhood variation for any of the age groups.

There are several possible reasons for these unexpected findings. Perceptions of land-use mix –rather than objective measures – might explain more of the observed between-neighbourhood variation of the age differences in WfT. Previous multilevel research noted perceived land-use mix diversity and accessibility as strong predictors of WfT for several age groups (Cerin et al., 2017, 2014; Shigematsu et al., 2009). Furthermore, those living in neighbourhoods with lower levels of land-use mix, but who perceived them as having higher land-use mix, were more likely to walk locally for transport (Koohsari et al., 2014).

It is also likely that all age groups are equally impacted in the same way by land-use mix, as proximity and mix of destinations has previously been strongly associated with WfTin both younger (McCormack et al., 2008) and older adults (Cerin et al., 2017). In our study (which categorised WfT as a binomial outcome, based on its distribution), land-use mix was not significantly associated with WfT. However, an earlier HABITAT Study noted that greater land-use mix was associated with more WfT, but only at high walking levels ($\geq$ 60 min per week) (Wilson et al., 2012), suggesting that the dichotomisation of WfT could have resulted in a loss of information. These results could also reflect methodological issues regarding the selected combination of land use codes, as varying the combination of land uses in the land-use mix calculation has shown to impact the strength of relationships with different types and amounts of walking (Christian et al., 2011).

Previous multilevel research has reported that pedestrian-friendly neighbourhoods characterised by residential density, street connectivity and land-use mix are more likely to motivate older adults to walk for transport (Cerin et al., 2017; Kamruzzaman et al., 2016; Van Cauwenberg et al., 2013). Our findings suggest that each factor individually (higher residential density and street connectivity only) might generate less age-related disparities in WfT across neighbourhoods.

Nevertheless, from an urban planning perspective, it is important to acknowledge the complexity of environmental influences on WfT; for example, density levels that are too high might negatively impact WfT. Perceived residential density was the only variable with a significant nonlinear association with $\geq$ 150 min of WfT in a large multi-country study (Kerr et al., 2015), which suggests the potential benefits of investigating residential density thresholds to inform the optimal density levels to increase WfT. Furthermore, the presence of residential density, street connectivity and land-use mix might have a combined effect on WfT, particularly in older adults (Van Cauwenberg et al., 2013) who might require higher levels of built environment support to walk for transport (McCormack and Shiell, 2011).

Additional built environment measures previously associated with WfT in older adults, but not explored in this study, might have further explained the age differences in WfT across neighbourhoods. These include walking infrastructure (quality and quantity of pedestrian paths), street lighting (a factor likely to influence natural surveillance as well as feelings of safety) (Van Cauwenberg et al., 2012) and access to public transport (Cerin et al., 2014). Increases in density of public transport have previously been associated with the likelihood of WfT in adults (Li et al., 2008; Suminski et al., 2005), and it is likely to facilitate the mobility of older adults who do not have access to a vehicle (Barnett et al., 2017).

Finally, the observed between-neighbourhood variation in WfT might have also been partially explained through social –rather than built– environment features, such as frequency of contacts with neighbours, neighbours' social support, or neighbourhood involvement, participation, and volunteering, each of which has been previously associated with WfT in older adults (Van Cauwenberg et al., 2014).

This study has a number of limitations. While the cross-sectional design of this study limits causal conclusions, adjustment for residential self-selection (which is rare among cross-sectional neighbourhood-based studies) (McCormack and Shiell, 2011; Barnett et al., 2017), ensured more reliable estimates of the influence of environmental exposures on WfT by accounting for individual-level bias (a regular transport walker might select a residence which facilitates their WfT), and controlled –to a certain extent– for possible reverse causation (McCormack and Shiell, 2011; Barnett et al., 2017; Forsyth et al., 2009; Talen and Koschinsky, 2013). WfT was self-reported, which is less accurate than objective measures of walking, as responses might reflect desirability and/or recall bias (particularly in older adults) (Yasunaga et al., 2008). However, objective measures lack the contextual aspects of walking, such as its purpose and location, unless combined with Global Positioning Systems (GPS) and applied algorithms (Cerin et al., 2014). While we adjusted for socioeconomic position, accounting for the income for different age groups, the time-budget component and different trip purposes were not considered, and could have affected WfT. Furthermore, the quality of the walking environment such as good pedestrian infrastructure (previously associated with more WfT) (Van Cauwenberg et al., 2012) and the spatial and geographical dimensions were not considered in our study.

Moreover, different neighbourhood boundaries vary in relevance depending on the type of PA studied (transport vs recreational walking) (Barnett et al., 2017) and across demographic populations (younger vs older adults) (Wendel-Vos et al., 2008; Sugiyama et al., 2012). In particular, the geographical scale chosen for measuring the objective built environment influences the strength of associations with WfT, with a 15 min walk from home being the most predictive of WfT, and weakest at the CCD scale (Learnihan et al., 2011). Therefore, our definition of *neighbourhood* using a census boundary (or CCD) might have weakened the associations with WfT, particularly considering that older adults might have a slower walking pace, and thus, the nearby environment might be more relevant for walking (Van Cauwenberg et al., 2011). Furthermore, while built environment exposures were developed based on those commonly used in the literature (Cerin et al., 2017), policy-derived exposures might have been more relevant in informing urban planning and policy that reduces age differences in WfT across neighbourhoods (Badland et al., 2017; Badland et al., 2015). Finally, the variation in pedestrian streetscapes across cities suggests that findings from single-city studies might not be generalisable (Thornton et al., 2016).

5. Conclusion

Based on previous research, adults experience increasing individual and environmental barriers to PA participation as they age due to declines in their physical function (Yen et al., 2009), and built environments seem to have a stronger influence on older adult's WfT (Cerin et al., 2017). The age disparity in PA participation is acknowledged within the World Health Organization's *Global age-friendly cities (*World Health Organization, 2007*)*, which calls for ecological evidence to inform age-responsive multilevel strategies to increase PA participation through active transportation opportunities.

Our study revealed that, on average, older adults walked less for transport than their younger counterparts. Consistent with a previous investigation (Ghani et al., 2016), however these average associations (commonly reported in the literature) seemed to across neighbourhoods, and older adults seemed more sensitive to their environments in regards to WfT. In Brisbane, denser and more connected environments generated less age differences in WfT. Therefore, increases in residential density and street connectivity in urban planning and policy may enable WfT in all neighbourhoods for all age groups, supporting healthy ageing in place. The present findings are particularly relevant within the context of the Brisbane City Council's *Brisbane Vision 2031* document (Brisbane City Council, 2031), which includes the promotion of *active, healthy communities* through an integrated transport system that enables the adoption of efficient, safe and sustainable travel choices by residents, including walking.

This study contributes to broader debates about the important role that neighbourhood design has in facilitating the healthy lifestyle of residents who are regularly exposed to it (Giles-Corti et al., 2016; Diez Roux and Mair, 2010). As previously advocated (Merlo, 2014), our results favor the ongoing longitudinal multilevel analyses of demographic heterogeneity around the neighbourhood averages, as they more realistically reflect the influence of neighbourhood exposures on the walking patterns of different population groups. Such investigations can inform the design of age-friendly neighbourhoods that might delay age-related declines in WfT, with resultant sustainable public health, socioeconomic and environmental gains for the overall population (Panter and Jones, 2010), ultimately supporting the WHO's objective of a global 10% reduction in the prevalence of physical inactivity by 2025 (World Health Organization, 2013) as well as the UN's Sustainable Development Goals (Medved, 2016).

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None declared.

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