The effects of built environment attributes on physical activity-related health and health care costs outcomes in Australia

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Abstract

Attributes of the built environment can positively influence physical activity of urban populations, which results in health and economic benefits. In this study, we derived scenarios from the literature for the association built environment-physical activity and used a mathematical model to translate improvements in physical activity to health-adjusted life years and health care costs. We modelled 28 scenarios representing a diverse range of built environment attributes including density, diversity of land use, availability of destinations, distance to transit, design and neighbourhood walkability. Our results indicated potential health gains in 20 of the 28 modelled built environment attributes. Health care cost savings due to prevented physical activity-related diseases ranged between A$2,800to A$99,600per 100,000 adults per year. On the other hand, additional health care costs of prolonged life years attributable to improvements in physical activity were nearly 50 percent higher than the estimated health care costs savings. Our results give an indication of the potential health benefits of investing in physical activity-friendly built environments.

Key Words

Built environment, physical activity, health, economic evaluation, health impact assessment

1 Introduction

In Australia, just over half of the adult population meets the recommended physical activity (PA) guidelines (Australian Bureau of Statistics 2015b). This is a public health concern, given the strong evidence of a causal association between low levels of physical activity and ischemic heart disease, stroke, colon cancer, breast cancer in women, and type 2 diabetes (Bull et al. 2004). The high prevalence of physical inactivity in Australia is taking its toll with nearly 10,000 premature deaths and 31,000 years lived with disability annually (Institute for Health Metrics and Evaluation 2015a). A physically inactive population also represents an economic burden for the society by means of high health care costs and loss of productivity (Pratt et al. 2012).

Population levels of physical activity could be increased via multilevel approaches that include the individual, institutional, community, and built and policy environments (Sallis et al. 2012). The built environment (BE), defined as those elements of the environment that are man-made, including transportation systems, urban planning, and individual buildings (World Health Organization 2009 p. 28), has drawn increasing attention to its effect on health. This is reflected in the exponential growth over recent years of studies investigating the links between physical activity and built environment attributes (Eichinger et al. 2015; Grasser et al. 2013; Kramer et al. 2013; McCormack & Shiell 2011; Van Holle et al. 2012). These studies have shed light on the effect of the built environment on levels of physical activity. However, demonstrating the potential health value of built environments that faciliatate physical activity may help to convince policy makers to consider health impacts in project appraisals.

In recent years, a number of quantitative studies have been conducted to predict health and economic outcomes of built environment interventions. Health impact assessment (HIA) studies mostly investigated hypothetical or policy scenarios, including health impacts via physical activity, air pollution, and road injuries. For example, Woodcock and colleagues developed the Integrated Transport and Health Impact Modelling (ITHIM) tool and applied it to assess transport and urban form scenarios in the United Kingdom (UK), Europe, India and the United States (Centre for Diet and Activity Research 2015). In one of the applications of ITHIM, three alternative urban land transport scenarios (low-carbon emission motor vehicles, increased active travel and a combination of both) were assessed for London, UK and Delhi, India (Woodcock et al. 2009). The findings from this study indicated that decreased use of motor vehicles and more active travel produced the highest health benefits with 7,332 averted disability-adjusted life years in London and 12,516 in Delhi on average per year per million population. A recent systematic review of HIAs and economic evaluations assessing mode shifts towards active transport found that in most of the included studies, health benefits from physical activity outweighed other potential health harms of active transport (e.g.

road injuries and greater exposure to air pollution) (Mueller et al. 2015). The literature in the field is now advancing towards more specific scenarios linking built environment to physical activity, followed by health impact assessments and economic evaluations as opposed to basing prediction on hypothetical scenarios. For instance, a recent study conducted cost-benefit analyses (CBAs) of proposed built environment changes designed to improve walkability in three different communities: one urban, one suburban, and one rural (Mansfield & Gibson 2015). In this study estimates for the association between a walkability score and sidewalk density were used to predict changes in walking for transport. The study found that the health benefits of the built environment projects exceeded the project costs in the urban area and the rural town, with benefit-cost ratios of 20.2 (95% CI: 8.7-30.6) and 4.7 (95% CI: 2.1-7.1). The suburban project's costs exceeded benefits by 40% (benefit-cost ratio= 0.6, 95% CI 0.3-0.9). Unlike the urban and rural projects, the suburban project involved only the installation of sidewalks, without other improvements such as addition of walking destinations, in an area that was lacking in destinations. Gibson and colleagues recently developed a simulation model linking changes in the built environment to time spent walking which was translated into health and economic outcomes (2015). The study results indicated potential economic benefits of US$ 234 million (95% CI: US$53-US$393 million) attributable to decreased mortality and diseases prevalence. A benefit-cost ratio of 29 (95% CI: 6.5-48) was estimated including only the cost of sidewalk infrastructure.

In Australia, building and maintaining healthy places has become a priority given the rising levels of chronic diseases (National Preventative Health Taskforce 2009). Creating healthy built environments is already on the agenda of health professionals, who are working closely with urban planners to influence city designs that support healthy lifestyles (Thompson, Kent & Lyons 2014). However, for the inclusion of physical activity in urban and transport projects, context specific estimates for the association built environment-physical activity, in combination with agreed methods to determine the health benefits of physical activity are required.

In this study, we quantified physical activity-related improvements in mortality and morbidity measured in health-adjusted life years (HALYs) associated with specific built environment attributes along with potential savings/increases in health care costs for the Australian context. The results can serve as a reference for the inclusion of physical activity-related health outcomes in the appraisal of built environment projects. This research originated as an initiative from the Centre for Population Health, Government of New South Wales (NSW), to demonstrate the potential costs and benefits of changes in urban form (built environment).

2 Methods

We reviewed the Australian literature assessing the association BE-PA for the adult population and used reported effect estimates to quantify the potential health benefits and health care costs associated with improving population levels of PA attributable to the BE. There are three sections to our analysis: (1) selection of BE attributes; (2) estimation of change in PA attributable to the BE expressed as average minutes of PA per week across the population; and (3) translation of changes in population levels of PA into HALYs gained and health care costs, using a mathematical model. We explain each step in turn (Figure 1).

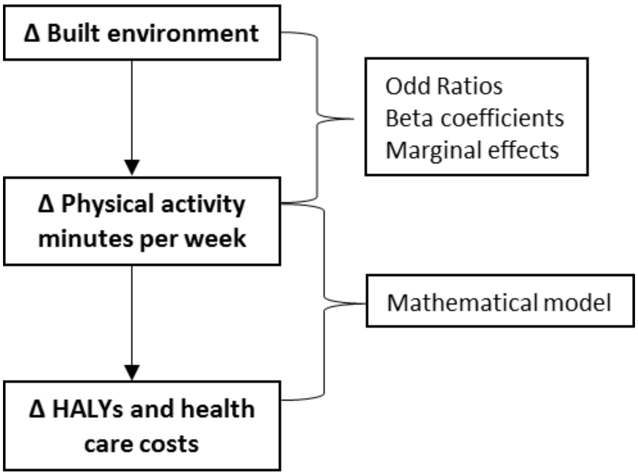

Figure 1 Analytical framework of the process of quantifying HALYs and health care costs of changes in exposure to selected built environment attributes.

Selection of built environment attributes

We reviewed the current Australian literature for the association BE-PA for the adult population (18 years +) (For complete review see Zapata-Diomedi and Veerman (2016)). Given the wide diversity of BE attributes reported, we grouped them in seven categories, including five of the six "D's" from Ewing and Cervero (2010) (density, diversity of land use, availability of destinations, distance to transit, and design) plus measures of safety and neighbourhood walkability. We assessed studies for the quality of their design, representativeness of the data, and control for confounding variables using tools applied for similar purposes (Grasser et al. 2013). We only modelled attributes from studies of good and fair quality that measured the BE objectively and were based on samples of over 1,000 individuals.

Estimation of changes in physical activity

Three types of measures for the association BE-PA were used in the source literature: (1) odds ratios for the likelihood of doing PA for a given BE exposure (Christian et al. 2011; Knuiman et al. 2014; Learnihan et al. 2011; Owen et al. 2010; Wilson et al. 2011); (2) beta coefficients for the additional time or sessions of PA for a given BE exposure (Giles-Corti et al. 2013; Koohsari et al. 2014; McCormack et al. 2012) and (3) marginal probabilities of doing PA for those exposed compared to non-exposed to a given BE attribute (McCormack et al. 2012). Given the diversity of reporting styles we applied different methods to translate effect estimates into average population change in minutes of PA per week.

Two steps were required to translate OR into average additional minutes of PA across the population. Firstly, we converted OR into relative risks (RR) to estimate the additional proportion doing PA if exposed to an alternative BE. We used the formula proposed by Grant (2014) which was developed by Zhang and Yu (1998) to convert OR to RR (Formula 1).

(1) $Relative\ Risk = \frac{Odds\ ratio}{(1-p_0+(p_0*Odds\ ratio))}$

Here, $p_0$is the incidence of the outcome of interest in the non-exposed group (physical activity among those not exposed to the built environment of interest). None of the source studies provided information for p_0, hence we assumed that this was equivalent to the prevalence of PA for the sample under consideration (sample prevalence physical activity in Table 4 in Results section). Our assumption is likely to be an over estimation of p_0 (we would expect that those not exposed would be less physically active), therefore we conducted a sensitivity analysis to explore the impact of alternative assumptions (see univariate sensitivity analysis). Secondly, we assumed that those taking up PA would increase the weekly dose to reach the level equivalent to the sample mean PA (sample weekly dose of physical activity in Table 4 in Results section). We conducted a sensitivity analysis to test our results to the assumption made on additional minutes (see univariate sensitivity analysis). RR and sample mean minutes of PA per week were then applied to calculate the change in average minutes of PA across the population (Formula 2). The first component of the left hand side of the formula indicates the additional proportion doing PA if exposed to an alternative BE which is then multiplied by the sample baseline minutes of PA to obtain the average change in minutes of PA across the population.

(2) $\Delta\ Average\ minutes\ of\ PA\ across\ the\ population = (RR * Sample\ prevalence\ PA - Sample\ prevalence\ PA) * Baseline\ minutes\ per\ week$

Beta coefficients were reported for three scenarios from two studies (Giles-Corti et al. 2013; Koohsari et al. 2014) and we interpreted them as the average increase in time/sessions of PA per week across the population for a given change in exposure. For instance, a study reported that every additional transport destination (Giles-Corti et al. 2013) within 800-1600 metres of a person's residence was associated with an average increase in 5.8 minutes of walking per week. In our scenario, we assumed that the whole population would have one such additional destination.

Thirdly, McCormack and colleagues (2012) reported the marginal effect of changes in the BE on the proportion of the population that did any walking, as well as the change in the average minutes per week walked among the walkers. Where this was the case, we incorporated both effects in our calculation of the change in minutes walked across the population.

A number of included studies presented effect sizes for more than one PA threshold (e.g. walk>30/60/90 mins/wk.), domain (PA for transport, recreation or both) or more than one model were used. All decisions regarding chosen effect sizes are presented in Table S1 of the Supplementary Material.

Mathematical model

We translated changes in average minutes of PA across the adult population into undiscounted HALYs using an updated version of the mathematical model developed for the Assessing Cost Effectiveness in Prevention (ACE-prevention) project (Cobiac, Vos & Barendregt 2009). Using 2010 as the base year, we discounted 3% per annum to health care costs (Gold 1996).The Supplementary Material (Section 2.2) gives a detailed description of the model and input parameters.

The mathematical model uses a macro simulation approach based on the proportional multi-state life table. It calculates changes in the occurrence of PA related diseases and 'health adjusted life years' (HALYs) (Barendregt et al. 1998). One HALY is the equivalent of one year in full health that is gained due to avoidance of disease (adjusted for severity) and postponement of death. The analysis is conducted by comparing health outcomes associated with a 'status quo' scenario against those in an alternative scenario in which PA levels are changed. Health outcomes were calculated from changes in the occurrence of diseases causally related to PA (ischemic heart disease, stroke, type 2 diabetes, breast cancer and colon cancer) (Danaei et al. 2009). Incidence rates for each disease are modified via potential impact fraction (PIF) calculations, which gives the proportional change in incidence as a function of a change in exposure, using the "relative risk shift" method (Barendregt & Veerman 2010) (See Figure S2 in the Supplementary Material). That is, rather than proportions moving to higher PA categories (e.g. from inactive to insufficiently active), the population remains in the same category (inactive, insufficiently active, etc.) but the risk of disease is reduced for that category. Changing incidence rates has an impact on the number of prevalent cases in the future and consequently mortality and years lived with disability (compared to the base case scenario). To calculate the PIF we used information for PA prevalence and RRs before and after an improvement in PA. Danaei et al. (2009) proposed a four-tier dose-response for PA and health outcomes: highly active (≥1,600 Metabolic Equivalents of Task minutes (MET-minutes)/wk. and 1h/wk of vigourous PA), recommended level active (600≤MET-minutes/wk. ≤1,600 and 1 h of vigorous PA/wk. or 2.5 h of moderate PA/wk.), insufficiently active (0<MET-minutes/wk. ≤600 or <2.5 h/wk of moderate PA) and inactive (no moderate or vigorous PA). PA prevalence was derived from mean minutes spent in a usual week doing moderate PA, vigorous PA, walking for transport and walking for recreation, with the included categories being mutually exclusive (Australian Bureau of Statistics 2015a). We translated population mean minutes of PA per week into MET-minutes, applying intensity values from the physical activity compendium (Ainsworth et al. 2011). We fitted linear functions to reported RRs (Danaei et al. 2009) with decreasing levels of risk associated with increasing levels of weekly energy expenditure (mean METs per week) (Cobiac, Vos & Barendregt 2009). We tested the sensitivity of our results by assuming an alternative non-linear dose-response function. The source studies lacked of information regarding likelihood of doing PA according to PA membership; hence we assumed that all groups (inactive, insufficiently active, etc.) increased PA equally. Furthermore, given the nature of our macro approach for modelling health outcomes we modelled the "average change in PA" rather than individual change. Those in the highly active group (≥1,600 MET-min/wk.) had a relative risk of one in the source literature, implying no additional benefit from extra physical activity (Danaei et al. 2009).

The model requires baseline age and sex specific epidemiological and demographic data, prevalence of the risk factor (PA), relative risks for PA related diseases, MET-minutes values and health care costs (Table 1). Given that type 2 diabetes is a risk factor for cardiovascular disease, relative risks were applied to incorporate the increased risk of ischemic heart disease and stroke among those with type 2 diabetes. To avoid double counting, we reduced the direct effect of PA on ischemic heart disease and stroke commensurately, using correction factors from the Global Burden of Disease (GBD) study (GBD 2013 Risk Factors Collaborators 2015). Health care costs for PA-related diseases were calculated by dividing total cost related to a disease by the number of incident cases (breast cancer and colon cancer) or prevalent cases (ischaemic heart disease, stroke and type 2 diabetes). Health care costs for the modelled diseases are from the original ACE-prevention study, which used data from the Disease Costs and Impact Study 2001 prepared by the Australian Institute of Health and Welfare, inflated with the Health Price Index (Australian Institute of Health and Welfare 2014).

Health care costs due to any other diseases that occur across the life course are estimated in the same fashion (if an intervention prolongs people's lives, they spend more in health care).

Table 1 Proportional multi-state life table inputs

Input parameter	Source
2010 mortality rates and population numbers	Australian Bureau of Statistics (2013, 2014)
2010 epidemiological data (prevalence, incidence, case fatality and mortality)[a]	Institute for Health Metrics and Evaluation (2015b)
Prevalence of physical activity (Supplementary Material Figure S3)	National Nutrition and Physical Activity Survey Basic Confidentialised Unit Record File (CURF) (Australian Bureau of Statistics 2015a)
Physical activity related diseases relative risk (Supplementary Material Table S2)	Danaei et al. (2009)
Relative risks of ischaemic heart disease and ischaemic stroke due to diabetes (Supplementary Material Table S2)	Asia Pacific Cohort Studies Collaboration (2003)
Mediating effect factors for diabetes in the association physical activity-ischemic heart disease/ischemic stroke	GBD 2013 study (GBD 2013 Risk Factors Collaborators 2015p. 711 Supplementary Material)
MET-minutes (walking 3.5 and cycling 5)	Ainsworth et al. (2011)
Health care costs (Supplementary Material Tables S3 and S4)	ACE-prevention study

a. *Epidemiological data* for the five physical activity related diseases (ischemic heart disease, stroke, type 2 diabetes, colon cancer and breast cancer in women) were derived with the help of DISMOD II (available free of charge at http://www.epigear.com/index_files/dismod_ii.html) to obtain data in metrics not explicitly reported (incidence and case fatality from prevalence and mortality).

Uncertainty and sensitivity analyses

Ninety-five percent uncertainty intervals were determined for all outcome measures by Monte Carlo simulation (2,000 iterations), using the Excel add-in tool Ersatz (Epigear, Version 1.33). Uncertainty parameters are presented in Table 2.

Table 2 Uncertainty parameters for evaluation health effects

Parameter	Mean (SE)	Distribution	Source
Relative Risks of diseases	See Table S2 in Supplementary Material	Normal (Ln RR)	Physical activity: (Danaei et al. 2009) Diabetes: (Asia Pacific Cohort Studies Collaboration 2003)
Health care costs	See Table S3 and S4 in Supplementary Material	Uniform	Australian Institute of Health and Welfare Impacts Study 2001. Maximum/minimum assumed at ±25% of mean value
Mediating effect diabetes on ischemic heart disease (IHD) and stroke	IHD: 0.14 (0.02) Stroke: 0.08 (0.03)	Normal	GBD 2013 Risk Factors Collaborators (2015p. 711 Supplementary Material)
Minutes per week	See Table 4	Lognormal	Koohsari et al. (2014); McCormack et al. (2012)
Odds ratios	See Table 4	Lognormal	See Table 4 studies reporting Odds ratios

We tested our results to the sensitivity of a number of assumptions we had to make given the lack of information provided in the studies reporting the modelled scenarios as well as decisions inherent to our mathematical model. To translate OR into additional minutes per week we made two assumptions, one on the p_0 value used in Formula 1 and the other on the additional minutes per week for those increasing PA. We tested the sensitivity of results of varying both parameters upwards and downwards. We also tested the sensitivity of our results to discounting HALYs and using a higher rate for health care costs.Given the increasing literature suggesting a curvilinear association for PA with specific diseases (Sattelmair et al. 2011) we modelled an alternative scenario assuming that PA is log linearly associated with a power transformation in MET minutes per week (0.75) (See Figures S4 and S5 in the Supplementary Material). Lastly, we produced estimates without taking into account the mediating effect of diabetes in the association PA-cardiovascular disease. A summary of sensitivity analyses performed is presented in Table 3.

Table 3 Univariate sensitivity analyses

Parameter	Base case	Sensitivity
Physical activity estimates		
Sample weekly dose of physical activity/Effect estimate[a]	See Table 4	±50%
p_0 (see formula 1)	Sample prevalence physical activity (see Table 4)	-20%
Mathematical model		
Discount rate health outcomes and health care costs	0% health and 3% health care costs per annum	3% health effects and 6% health care costs (Tan-Torres Edejer 2003)
PA RR	Linear	Log-linear with power transformation of MET-mins/wk.
Potential impact factor	N/A	Exclude mediation effect of diabetes in the association physical activity-cardiovascular disease

N.B 1000 iterations for Monte Carlo simulation

a. In the study by Giles-Corti et al. 2013 only p-values were reported from which we could not derive uncertainty parameters, hence we applied sensitivity analysis to the additional minutes per week as a result of increases in the number of destinations.

3 Results

Scenarios

We modelled a total of 28 scenarios from eight studies (Christian et al. 2011; Giles-Corti et al. 2013; Knuiman et al. 2014; Koohsari et al. 2014; Learnihan et al. 2011; McCormack et al. 2012; Owen et al. 2010; Wilson et al. 2011) in density (n=3), diversity (n=2), design (n=7), destinations (n=6), distance to transit (n=4) and walkability indices (n=6). No studies for the safety category met the inclusion criteria. We present evaluated scenarios in Table 4 (e.g., density, diversity, etc.), detailing the change in the built environment assessed (see Supplementary Material Table S5 for studies' details). Besides, we provide information on the outcome measured in the scenarios (e.g. walking, cycling) and measures of effect (odds ratios, beta coefficients and marginal effects + beta coefficients). Reported baseline data for the sample prevalence of PA and sample weekly dose of PA served to translate OR to additional minutes of PA per week as explained in the methods section.

Table 4 Built environment attributes modelled

Category	Scenario/Study/Location	Change in built environment attribute	Outcome	Measure of effect	Effect estimate (SE)	Baseline data: Sample prevalence physical activity	Baseline data: Sample weekly dose of physical activity
DENSITY	Density/ Christian et al. (2011)/Perth (WA)	Density standardised to z-scores. One unit increase in density (1 SD) represents an increase of 8 dwellers per ha.[d] within a participant's 1.6 km network service area	Any walking	Odds Ratio	1.04 (0.06)[a]	62%	93.5
	Density/Knuiman et al. (2014)/Perth (WA)	Density standardised to z-scores. One unit increase in density (1 SD) represents an increase of 8 dwellers per ha.[e] within a participant's 1.6 km network service area	Walking for transport	Odds Ratio	0.96 (0.09)[a]	33%	18.75[f]
	Density/Wilson et al (2011)/Brisbane (QLD)	Decrease from 9205 (mean lowest quintile) to 650 (mean highest quintile) average size of residential zone land[e] within a one-kilometre radius of participant's residence	Any walking	Odds Ratio	1.37 (0.12)[a]	23%	30[g]
DIVERSITY	Land use mix (LUM)[i]/Christian et al. (2011)/Perth (WA)	LUM standardised to z-scores. One unit increase in the LUM represents an increase in 0.15 units in diversity[d] within a participant's 1.6 km network service area	Walking for transport	Odds Ratio	1.15 (0.05)[a]	26 %	26
	LUM[i]/Knuiman et al. (2014)/Perth (WA)	LUM standardised to z-scores. One unit increase in the LUM represents an increase in 0.15 units in diversity[e] within a participant's 1.6 km network service area	Walking for transport	Odds Ratio	1.33 (0.07)[a]	33%	18.75[f]
DESIGN	Connectivity/ Christian et al. (2011)/Perth (WA)	Connectivity standardized to z-scores. One unit increase represents an increase of 18 three or more ways intersections per km^2 [d] within a participant's 1.6 km network service area	Walking for transport	Odds Ratio	1.15 (0.06)[a]	26 %	26

	Connectivity/ Koohsari et al. (2014)/Adelaide (SA)	Increase from 1 to 10 intersections (3-way or more) per km^2. Mean 245 (range 12 to 901) within a participant's Census Collection Districts (CCD) area.	Walking for transport	Beta coefficient	0.27 (0.06)[b]		
	Connectivity/ Knuiman et al. (2014)/Perth (WA)	Connectivity standardized to z-scores. One unit increase represents an increase of 18 three or more ways intersections per km^2 [e] within a participant's 1.6 km network service area	Walking for transport	Odds Ratio	1.13 (0.06) [a]	33%	18.75 [f]
	Connectivity/ Wilson et al (2011)/Brisbane (QLD)	Increase from 4 (mean lowest quintile) to 51 (mean highest quintile) 4-way intersections[e] within a one-kilometre radius of participant's residence	Any walking	Odds Ratio	1.44 (0.13) [a]	23% (43%)	30[g]
	Sidewalks/ McCormack et al. (2012)/Perth (WA)	10 km. increase in sidewalk availability within a participant's 1.6 km network service area	Transport walking	Marginal effect +Beta coefficient	2.97%[c], 5.38 (3.01)[c]		
	Off road bikeways/Wilson et al (2011)/Brisbane (QLD)	Increase from 0 km. (mean lowest quintile) to 7 km. (mean highest quintile) of off road bikeways[e] within a one-kilometre radius of participant's residence	Any walking	Odds Ratio	1.34 (0.11) [a]	23%	30[g]
	Street lights/Wilson et al (2011)/Brisbane (QLD)	Increase from 315 (mean lowest quintile) to 783 (mean highest quintile) of street lights within a one-kilometre radius of participant's residence	Any walking	Odds Ratio	1.25 (0.12) [a]	23%	30[g]
DESTINATIONS	Transport destinations/ Giles-Corti et al. (2013)/Perth (WA)	Per increase in one transport destination (after relocation)/ Post office, bus stops, delicatessens, supermarkets within 800 m of participant's residence and train stations, shopping centres or CD and DVD stores within 1.6 km	Transport walking	Beta coefficient	5.8[h]		
	Recreation destinations/ Giles-Corti et al. (2013)/Perth (WA)	Per increase in one recreational destination (after relocation)/ Beaches within 800 m of participant's residence and parks and sport fields within 1.6 km	Recreational walking	Beta coefficient	17.6[h]		
	Distance to retail/Wilson et al. (2011)/Brisbane (QLD)	From a retail zone within >1 km to one within >0.2 km within the street network distance in kilometres from a participant's residence	Any walking	Odds Ratio	1.46 (0.13) [a]	23%	30[g]
	Distance to parks/Wilson et al. (2011)/Brisbane (QLD)	From a park zone land within >1 km to one within >0.2 km within the street network distance in kilometres from a participant's residence	Any walking	Odds Ratio	1.08 (0.13) [a]	23%	30[g]
	Destinations/ Knuiman et al. (2014)/Perth (WA)	From =<3 to 4-7 general destinations (services, convenience stores and public open spaces)	Transport walking	Odds Ratio	1.08 (0.15) [a]	33%	18.75 [f]

		accessible along the street network within 1.6 km from participant's residence					
	Destinations/ Knuiman et al. (2014)/Perth (WA)	From =<3 to 5-15 general destinations (services, convenience stores and public open spaces) accessible along the street network within 1.6 km from participant's residence	Transport walking	Odds Ratio	1.40 (0.21) [a]	33%	18.75 [f]
DISTANCE TO TRANSIT	Bus stops/Knuiman et al. (2014)/Perth (WA)	From 0-14 to 5-19 general destinations bus stops accessible along the street network within 1.6 km from participant's residence	Transport walking	Odds Ratio	1.99 (0.16) [a]	33%	18.75 [f]
	Bus stops/ Knuiman et al. (2014)/Perth (WA)	From 0-14 to =>30 general destinations bus stops accessible along the street network within 1.6 km from participant's residence	Transport walking	Odds Ratio	2.33 (0.20) [a]	33%	18.75 [f]
	Train station/ Knuiman et al. (2014)/Perth (WA)	Train station accessible along the street network within 1.6 km from participant's residence	Transport walking	Odds Ratio	1.79 (0.29) [a]	33%	18.75 [f]
	Transit stops/ Wilson et al. (2011)/Brisbane (QLD)	Access to the nearest transit stop within >0.2 km compared to >1 km within the street network distance in kilometres from a participant's residence	Any walking	Odds Ratio	1.34 (0.16) [a]	23%	30[g]
WALKABILITY INDEX	Walkability index[j]/ Christian et al. (2011)/Perth (WA)	Increase in one unit in the index (z-score) within a participant's 1.6 km network service area	Any walking	Odds Ratio	1.06 (0.02) [a]	62%	93.5
	Walkability index[k]- Suburb/Learnihan (2011)/Perth (WA)	Highly walkable compared to low within a participant's suburb area	Transport walking	Odds Ratio	1.63 (0.15) [a]	36%	26
	Walkability index[k]- Census Collection District (CCD) scale/Learnihan (2011)/Perth (WA)	Highly walkable compared to low within a participant's CCD area	Transport walking	Odds Ratio	2.07 (0.13) [a]	36%	26
	Walkability index[k]-15 mins walk scale/ Learnihan (2011)/Perth (WA)	Highly walkable compared to low within a participant's 15 minutes walking area	Transport walking	Odds Ratio	2.79 (0.15) [a]	36%	26
	Walkability index[j]/ McCormack et al. (2012)/Perth (WA)	Increase in one unit in the index (z-score) within a participant's 1.6 km network service area	Transport walking	Marginal effect +Beta coefficient	2.16%[c] , 3.32 (6.21)[c]		

Walkability index[k]/Owen et al. (2010)/Adelaide (SA)	High compared to low within a participant's CCD area	Any cycling	Odds Ratio	1.82 (0.19)[a]	14%	10

a. Odds ratio (OR) (SE(lnOR)). Standard errors were estimated from the confidence interval applying the formula proposed on page 33 of Ersatz user guide (Barendregt 2012).
b. β coefficient from negative binomial regression converted into additional minutes per week by multiplying by 10 which represented the minimum walking time for a trip (outcome assessed). Similar procedure was followed to estimate the standard error (Koohsari et al. 2014).
c. Two stage modelling approach: Probit regression to estimate marginal probabilities followed by OLS to estimate β for additional walking minutes (McCormack et al. 2012).
d. We assumed that the information provided by Knuiman et al. for the value of 1SD applies here as both studies are based on the same data set (RESIDential Environment Study (RESIDE)).
e. Study authors provided information for the value of the mean and SD of the built environment attributes assessed.
f. Average trips over 4 data collections by trip time of 15 minutes (Knuiman et al. 2014).
g. Lower bound walking range assessed (see Table S1 Supplementary Saterial).
h. β coefficient from Generalize Linear Mixed Models representing the effect of one unit change in the continuous independent variable on the continuous outcome (walking).
i. LUM includes the following land uses: 'Residential', 'Retail', 'Office', 'Health, welfare and community' and 'Entertainment, culture and recreation' land use classes (Christian et al. 2011).
j. Walkability index based on three built environment characteristics: residential density, street connectivity and land use mix.
k. Walkability index based on four built environment characteristics: residential density, street connectivity, land use mix and retail floor area.
WA: Western Australia; QLD: Queensland; SA: South Australia

Health outcomes

In the following paragraphs we present findings per 100,000 adults per year for HALYs gained for the 28 evaluated scenarios. There was large variability in the results, most of which can be attributed to the different reporting methods in the source literature for the association BE-PA. All results are presented in Table 5 and discussed in the following paragraphs.

Density

Only one of the three density scenarios indicated statistically significant results for health outcomes, with estimated HALYs gained of 1.98 for a decrease from 9,205m^2 to 650m^2 of average residential zone land per hectare (10,000 m^2) (Wilson et al.'s scenario). Wilson and colleagues' scenario represents approximately an increase from 1 to 15 dwellings/ha.[1], which is considerably higher than the increase in 8 dwelling/ha. for the scenarios from Knuiman et al. and Christian and colleagues. Despite the scenarios derived from Knuiman and co-authors and Christian et al. being based on the same study (RESIDential Environment Study (RESIDE)), their results differed. One possible explanation is that Knuiman et al. evaluated walking for transport whereas for Christian and co-authors we used estimates for walking for any purpose (see Table S1 of the Supplementary Material). Further, the estimate from Knuiman et al. was based on longitudinal data collected over four waves whereas Christian et al. used baseline data.

Diversity

On average, an improvement in diversity represented by one unit increase in the composite measure of LUM, within the area of 1.6 km street network from a participant's residence, could potentially accrue 0.94 HALYS gained (scenario derived from Christian et al.) to 1.37 (scenario derived from Knuiman et al.). The interpretation of improvement in LUM is rather difficult. However, the source information did not allow us to translate such change into an explicit scenario (see explanation i from Table 4). While both estimates of effect of LUM on PA are based on the same study, the same conceptual definition of LUM, and the same physical activity outcome (walking for transport), the results are different. The odds ratio from the longitudinal analysis by Knuiman and colleagues (see Table 4) and prevalence of walking for transport at the baseline are greater to those in the cross-sectional study by Christian et al. This implies a greater proportion taking up walking for transport in the scenarios based on the analysis by Knuiman et al. However, the additional weekly dose of

[1] If the average residential land size is 650m^2, there would be approximately 15 houses in a hectare (10,000/650=15.38), whereas only one house fits in a hectare for an average land size of 9,205m2 (10,000/9250=1.08),

transport in the scenario derived from Knuiman and co-authors is smaller than that in the scenario resulting from Christian et al.

Design

Seven scenarios for measures of design were evaluated, including connectivity (the number of intersections within an area), availability of sidewalks or bikeways, and number of street lights. The average HALYs gained from improvements in connectivity ranged from 0.56 for an increase of 18 three- or more- way intersections per km^2 (scenario derived from Knuiman et al.) to 3.03 for an increase from 1 to 10 three- or more- ways intersections per km^2 (scenario derived from Koohsari et al.). In Wilson et al. walking for any purpose was evaluated, whereas in the rest of the scenarios the outcome was walking for transport purposes. The mean HALYs gained for increases in the availability of sidewalks and off-road bikeways ranged from 1.85 for a change in the availability of bikeways from none to 7 km (scenario derived from Wilson et al.'s study) to 4.82 for an additional 10 km of sidewalk (scenario resulting from McCormack et al.'s analysis) within the neighbourhood area defined in the source studies. In the scenario by McCormack and colleagues, walking for transport was evaluated, whereas any walking was the outcome in Wilson et al.'s analysis. Lastly, an improvement in street lights from 315 to 783 within 1 km from a participant's residence accrues on average 1.36 HALYs gained (Wilston et al.) as a result of improvements in walking for any purpose. However, the estimate for Wilson et al.'s scenario includes 0 in the uncertainty interval.

Destinations

Improvements in walking for transport, in the scenarioderived from Giles-Corti, resulted in HALYs gains of 6.53 for an increase in one transport destination within the area of 1.6 km street network from a participant's residence. Increasing general destinations was not associated with statistically significant changes in walking based on Knuiman et al.'s scenarios. Providing an additional recreational destination within 1.6 km street network from residence accrues 19.81 HALYs in the scenario based on Giles Corti and colleagues' study. In Wilson et al., having a retail zone within less than 0.2 km compared to less than 1 km results in potential HALYs gained of 2.45. Also, Wilson et al. provided a scenario for an improvement in access to park land, from one within 1 km to one within less than 0.2 km, however, they did not find a statistically significant association.

Distance to transit

Two of the three scenarios derived from Knuiman et al. for improvements in the availability of transit stops indicated health benefits due to increased walking for transport. Increasing the availability of bus stops, from less than 14 to 15-19 within 1.6 km street network from residence, translates into HALYs gained of 3.39. Slightly higher HALY gains of 4.14 can be achieved if the improvement is up to more than 30 bus stops.

Walkability

All six evaluated scenarios indicated health benefits in terms of HALYS gained for improvements in measures of walkability within the studies' defined neighbourhood areas. Average values from improvements in walking for transport, ranged from 3.23 HALYs for an increase in one unit in the standardised walkability index for the scenario derived from McCormack et al.'s, to 7.2 for an improvement from low to high walkability in the scenario resulting from Learnihan and colleagues' analysis (15 minutes area scale). In Christian et al., an increase in one unit in the standardised walkability index would potentially accrue on average 1.44 HALYs due to improvements in walking for any purpose. Lastly, in Owen and co-authors benefits from improvements in cycling were modelled, with results indicating HALY gains of 1.56 for a change from low to high walkability.

Health care costs

Savings in health care costs per year for PA-related diseases ranged from A$1,558 to A$99,568per 100,000 adults. On the other hand, health care costs in added life years were approximately 50% higher than the savings obtained by having to treat fewer cases of PA related disease in earlier years, even after discounting at 3% (Table 5). It is important to note that there is great uncertainty in the health care costs estimates.

Table 5 HALYs, health care costs savings and health care costs in added life years per 100,000 people per year for built environment scenarios

Changes in built environment attribute	HALYs	Health care costs (A$ 2010)[a]	Health care costs in added life years (A$ 2010)[a]
Density. + 1 SD (Christian et al. 2011)	0.95 (-1.75 to 3.7)	-$4,713 (-$21,286 to $9,380)	$6,836 (-$12,808 to $28,544)
Density. + 1 SD (Knuiman et al. 2014)	-0.17 (-1.01 to 0.72)	$813 (-$3,784 to $5,754)	-$1,182 (-$7,490 to $5,173)
Density. From 650 sqm2 to 9205 sqm2 average size of residential zone land within 1 km radius of residence (Wilson et al. 2011)	1.98 (0.33 to 3.75)	-$9,837 (-$22,844 to $875)	$14,200 ($1,481 to $28,946)
Land use mix. + 1 SD (Christian et al. 2011)	0.94 (0.24 to 1.71)	-$4,634 (-$10,158 to $420)	$6,703 ($870 to $12,986)
Land use mix. + 1 SD (Knuiman et al. 2014)	1.37 (0.65 to 2.11)	-$6,813 (-$13,186 to $434)	$9,851 ($2,651 to $16,316)
Connectivity. + 1 SD (Christian et al. 2011)	0.94 (0.19 to 1.69)	-$4,642 (-$10,306 to $487)	$6,695 ($741 to $13,121)
Connectivity. Increase from 1 to 10 intersections (3-way or more) (Koohsari et al. 2014)	3.03 (2.29 to 3.43)	-$15,028 (-$23,449 to $1093)	$21,729 ($7,362 to $27,232)
Connectivity. + 1 SD (Knuiman et al. 2014)	0.56 (0.02 to 1.09)	-$2,790 (-$6,478 to $449)	$4,036 (-$113 to $8,378)
Connectivity. From 4 to 51 four-way intersections (Wilson et al 2011)	2.34 (0.64 to 4.22)	-$11,662 (-$25,706 to $692)	$16,836 ($2,463 to $32,579)
Sidewalk. 10 km increase in sidewalk. (McComack et al. 2012)	4.82 (2.91 to 8.65)	-$24,224 (-$52,545 to $32)	$34,653 ($11,337 to $65,230)
Bikeways. From 0 km to 7km (mean highest quintile) of off road bikeways (Wilson et al 2011)	1.85 (0.41 to 3.47)	-$9,150 (-$20,974 to $708)	$13,215 ($1,674 to $26,576)
Street lights. From 315 to 783 street lights (Wilson et al 2011)	1.36 (-0.13 to 3.05)	-$6,732 (-$17,833 to $1699)	$9,722 (-$1,251 to $23,179)
Destinations. + 1 transport destination (Giles-Corti et al. 2013)	6.53 (5.02 to 7.25)	-$32,812 (-$50,726 to $45)	$46,971 ($16,988 to $57,660)
Destinations. + 1 recreational destination (Giles-Corti et al. 2013)	19.81 (15.22 to 22.01)	-$99,568 (-$153,929 to $130)	$142,537 ($51,560 to $174,973)
Destinations. From retail zone land within >1km to >0.2km (Wilson et al. 2011)	2.45 (0.74 to 4.4)	-$12,189 (-$26,972 to $857)	$17,609 ($3,411 to $34,273)
Destinations. From park zone land within >1km to >0.2km (Wilson et al. 2011)	0.44 (-1.04 to 2.13)	-$2,228 (-$12,429 to $5458)	$3,175 (-$7,444 to $15,693)

Changes in built environment attribute	HALYs	Health care costs (A$ 2010)[a]	Health care costs in added life years (A$ 2010)[a]
Destinations. From =<3 to 4-7 (Knuiman et al. 2014)	0.32 (-1.09 to 1.82)	-$1,558 (-$10,026 to $5851)	$2,282 (-$8,013 to $13,904)
Destinations. From =<3 to 8-15 (Knuiman et al. 2014)	1.56 (-0.52 to 3.73)	-$7,735 (-$21,746 to $3514)	$11,200 (-$3,971 to $28,523)
Bus stops. From 0-14 to 15-19 (Knuiman et al. 2014)	3.39 (1.67 to 5.22)	-$16,852 (-$31,583 to $1168)	$24,342 ($6,754 to $39,916)
Bus stops. From 0-14 to =>30 (Knuiman et al. 2014)	4.14 (2.02 to 6.33)	-$20,546 (-$39,917 to $1686)	$29,656 ($8,697 to $48,995)
Train station. Railway station present within 1.6km compared to no rail way station (Knuiman et al. 2014)	2.74 (-0.12 to 5.83)	-$13,630 (-$34,381 to $3616)	$19,691 (-$1,404 to $44,171)
Transit stop. From one within >1km to one within >0.2km (Wilson et al. 2011)	1.87 (-0.25 to 4.47)	-$9,320 (-$25,001 to $2598)	$13,473 (-$1,972 to $33,758)
Walkability index. + 1SD (Christian at al. 2011)	1.44 (0.28 to 2.67)	-$7,119 (-$15,704 to $755)	$10,312 ($1,270 to $20,446)
Walkability index neighbourhood scale. High walkable compared to low (Learnihan et al. 2011)	3.36 (1.2 to 5.55)	-$16,704 (-$33,948 to $800)	$24,086 ($4,054 to $42,223)
Walkability index CCD scale. High walkable compared to low (Learnihan et al. 2011)	5.12 (2.94 to 7.24)	-$25,446 (-$45,885 to $1787)	$36,754 ($11,128 to $55,864)
Walkability index 15 minutes area scale. High walkable compared to low (Learnihan et al. 2011)	7.2 (4.78 to 9.58)	-$35,737 (-$61,919 to $2692)	$51,646 ($16,012 to $74,379)
Walkability index. + 1SD (McCormack et al. 2012)	3.23 (1.63 to 8.89)	-$16,156 (-$46,915 to $20)	$23,170 ($6,143 to $65,448)
Walkability index. High walkable compared to low (Owen et al. 2010)	1.56 (0.45 to 2.91)	-$7,744 (-$17,630 to $622)	$11,180 ($1,834 to $22,081)

a. Negative figures represent costs savings

3.1 Results from sensitivity analyses

The results are sensitive to some of the assumptions made in this study. Firstly, results are sensitive to the assumption around the number of additional minutes per week for scenarios derived from studies reporting odds ratios. Increasing or decreasing the dose of physical activity for those taking up walking or cycling as a result of a change in the built environment by 50%, translates to proportional changes in the estimated health and health care costs values (Tables S6 and S7 of the Supplementary Material). Similar sensitivity results were obtained from scenarios derived from studies reporting beta coefficients for which we did not have uncertainty parameters (destinations scenarios from Giles-Corti et al.). A lower value for p_0 (20% lower) (incidence physical activity in the non-exposed) used in the formula to translate odds ratios into relative risks resulted in an upper variation in the estimated values ranging from 5% to 33% (Supplementary Material Table S8). Notably, the scenarios for density and walkability derived from Christian et al. were the most sensitive, which can be attributed to the high level of p_0 (refer to Table 4 Sample prevalence physical activity). Excluding the mediating effect of diabetes on cardiovascular diseases results in slightly higher estimates, 9% for HALYs gained and PA-health care costs savings and 10% for health care costs in added life years (Supplementary Material Table S9). Applying a 3% per annum discount rate for health outcomes results into a decrease of 40% in potential HALYs gained (Supplementary Material Table S10). Discounting health care costs at a higher rate (6%) results in lower estimates ranging from 20% to 35% (Table S11 Supplementary Material). Lastly, changing the shape of the dose response function for PA with health outcomes to a curvilinear dose-response has a major impact with results doubling in some cases (Supplementary Material Table S12).

4 Discussion

To our knowledge, this is the first study that attempts to estimate the potential health gains and health care cost savings associated with specific attributes of the built environment for the Australian context. Past studies specific to Australia provided general estimates of economic value per kilometre walked or cycled that included both mortality and morbidity measures of improvements in PA (Mulley et al. 2013; Transport for New South Wales 2013). However, these general estimates do not specify what built environment attributes need to be targeted to achieve these benefits. The results from our research add to the existing literature by producing a series of health and economic values for specific changes to the built environment based on well-established methods of the proportional multi-state life table (Barendregt et al. 1998). Our estimates could be used to incorporate the value of physical activity-related health outcomes in HIAs and economic evaluations of interventions to the built environment.

Overall, 20 of the 28 modelled scenarios indicated potential annual health benefits represented by HALYs gained per 100,000 adults per year. Most of the health benefits in terms of HALYs gained presented in Table 5 ranged from 1 to 7 per 100,000 adults exposed to an improvement in the built environment per year. The greatest majority of results for savings in health care costs of improvements in PA related disease ranged between A$4,634 and A$35,737 per 100,000 adults per year. Additional health care costs in added life years ranged mostly between A$9,851 and A$51,646 per 100,000 people (+18) per year. Our estimates are specific to the data collection areas in three main Australian cities (Brisbane, Perth and Adelaide). However, in the absence of locally derived alternatives, they could be used as a reference for other metropolitan areas with similar characteristics.

To our knowledge, no other studies have evaluated the potential health outcomes in terms of health-adjusted life years of improvements in the BE. Boarnet, Greenwald and McMillan (2008) did perform an analysis that had mortality as outcome measure. They used regression analysis on travel survey data from Portland, Oregon, to quantify the impact of built environment attributes (population/jobs density, number of intersections and distance to business centre) on distance walked and translated improvements in walking to lives saved. Their results suggested that at a minimum 0.0031 to 0.0912 lives per 1000 people per year would be saved from improvements in the BE towards more walkable places. These figures translate into 0.31 to 9.12 lives saved per year per 100,000 people. Even though our estimates are not directly comparable as we adjust life years gained for disability, these include the range estimated by Boarnet and colleagues.

Quantifying the potential health and health care costs attributable to improvements in the BE involved a number of challenging assumptions. To assess the potential impact on results of these assumptions, we conducted an extensive sensitivity analysis. The greatest majority of studies reported results in terms of the odds of doing physical activity for those exposed to the assessed BE feature, compared to those not exposed, without indicating the dose. The only exception was the study by McCormack et al. (2012), which assessed not only the marginal probability for an individual walking if exposed to an environmental attribute, but also the change in the average weekly dose among those walking. As presented in our sensitivity results, our estimates are highly sensitive to the assumption of the dose of PA for scenarios derived from studies reporting odds ratios. Our estimates are also sensitive to discounting HALYs and variations in the discounting rate for health care costs. However, the choice of discount rate is dependent on the agency carrying out the evaluations, hence; it is not an issue of empirical uncertainty but of choice. Whether health should be discounted has been debated in the past, with some literature suggesting applying the same rate as cost as well as conducting sensitivity analyses (Gold 1996) while others recommend not discounting health outcomes (Murray et al. 2012). Discounting the future is a common practice for monetary costs to account for people's time preference (individuals would rather have something good today than something good in the future, and the reverse for something bad) (Commonwealth of Australia 2006; Drummond et al. 2005), but is controversial when applied to the health of others, or of future generations. Applying alternative dose-response function for the effect of physical activity on health outcomes has a great impact on results. However, past studies also indicated major variations in results depending on the dose-response function used (Woodcock, Givoni & Morgan 2013).

Some further limitations related of this study should be discussed. Firstly, the diversity in the ways in which different studies report their findings for the relationship of built environment with physical activity outcomes hinders direct comparison and pooling, and in some cases insufficient information is provided to enable meaningful interpretation. The use of more uniform measurement methods for both exposure (instruments used and domains measured) and physical activity would facilitate pooling and comparability of results. Furthermore, the great variability of measurements methods and results of PA exposure has a large impact in our estimated results. Secondly, there is potentially some imprecision in the measurement of exposure in the source studies, which leads to 'regression dilution bias', that is, improved measurement of relevant exposures (i.e., BE attributes) may lead to larger, more precise effect estimates. A further limitation is that the greatest majority of scenarios are based on cross-sectional studies, which does not allow for a direct causal interpretation. The association can be due to the built environment influencing physical activity; this is the hypothesis underlying this research. Alternatively, it could be due to physically active people choosing to live in neighbourhoods that facilitate that behaviour. By adjusting for self-selection, some studies try to avoid this 'reverse causal' interpretation. McCormack and Shiell (2011) systematically reviewed the international literature for the relationship BE-PA and found that adjusting for self-selection tended to diminish the strength of the associations, but only to a small extent. Nonetheless, the associations could be due to other (observed or unobserved) factors causing both (confounding). Most studies use statistical adjustment to minimise the impact of measured factors. From the literature we do not know whether those taking up physical activity due to an intervention may respond by simultaneously reducing other forms of physical activity. Along this analysis, we made the assumption that there was no substitution effect, as has been done in the past (Boarnet, Greenwald & McMillan 2008). In our model, the proportion of the population that is sufficiently active (~25%) receives no benefit from additional physical activity, which may led to underestimation of health impact. Also, there is growing evidence suggesting a causal association between PA and dementia which were not included in our estimates resulting into a potential under estimation of outcomes (Blondell, Hammersley-Mather & Veerman 2014; Hamer & Chida 2009).

Conclusion

In this research we produced estimates for the physical activity-related health benefits of specific built environment attributes, and the economic value in terms of health care costs these represent. To our knowledge, there has been no study in the past that has attempted to demonstrate the potential health and economic value of such a broad range of specific built environment attributes. The results of this study can be incorporated into health impact assessments and cost-benefit analyses conducted to inform infrastructural developments.

5 Competing interest

None to declare

6 Authors' contribution

BZD and JLV developed the design of the study and BZD developed the methods supervised by JLV. BZD ran, interpreted and wrote the first draft of the main document and supplementary materials and JLV commented on the paper. BZD and JLV co-edited all sections. AMMH provided epidemiological estimates for health model and revised first submission of the manuscript.

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