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# **Longitudinal relationship between home and neighbourhood physical environment typologies and physical activity across early to middle childhood**

Findings from the PLAYCE cohort study

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## Research Summary

### Why was the research done?

The built environment plays a key role in shaping children's opportunities to be physically active; however, few studies have integrated objective and parent-perceived built environment measures to derive data-driven neighbourhood typologies and examine longitudinal associations with device-measured movement behaviours across developmental stages.

### What were the key findings?

Longitudinal associations between movement behaviours and neighbourhood typologies across early to middle childhood were examined using data from the PLAYCE (Play Spaces and Environments for Children's Physical Activity) cohort (n=569; aged 2-10 years). Movement behaviours were measured using accelerometers and classified using a machine-learning model. Six neighbourhood physical environment profiles identified in a previous study using latent profile analysis were applied.

Across all profiles, most movement behaviours showed non-linear age trajectories except for walking. Differences between physical environment profiles were consistent across ages and sexes. Children living in 'semi-rural' neighbourhoods accumulated more walking time than those in other profiles, and more total daily physical activity and light-intensity play than all profiles except those characterised by higher access to blue space. Profiles characterised by higher residential density, greater traffic exposure, and limited private yard space were associated with lower levels of energetic play and walking, despite relatively good access to public transport and destinations.

### What does this mean for policy and practice?

Neighbourhoods offering access to private outdoor space, natural environments, and lower traffic exposure appear to support physical activity across early to middle childhood. Urban planning and housing policies should prioritise child-friendly design features, such as access to play space, nature, and low traffic exposure, to promote opportunities for physical activity from early life.

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We acknowledge the Traditional Custodians of the lands on which we work and live across Australia.  
We pay our respects to Elders past and present and recognise their continued connections  
to land, sea and community.

## Abstract

The built environment plays a key role in shaping children's opportunities to be physically active; however, few studies have integrated objective and parent-perceived built environment measures to derive data-driven neighbourhood typologies and examine longitudinal associations with device-measured movement behaviours across developmental stages.

Longitudinal associations between movement behaviours and neighbourhood typologies across early to middle childhood were examined using data from the PLAYCE (Play Spaces and Environments for Children's Physical Activity) cohort (n=569; aged 2-10 years). Movement behaviours were measured using accelerometers and classified using a machine-learning model. Six neighbourhood physical environment profiles identified in a previous study using latent profile analysis were applied.

Across all profiles, most movement behaviours showed non-linear age trajectories except for walking.

Differences between physical environment profiles were consistent across ages and sexes. Children living in 'semi-rural' neighbourhoods accumulated more walking time than those in other profiles, and more total daily physical activity and light-intensity play than all profiles except those characterised by higher access to blue space. Profiles characterised by higher residential density, greater traffic exposure, and limited private yard space were associated with lower levels of energetic play and walking, despite relatively good access to public transport and destinations.

Neighbourhoods offering access to private outdoor space, natural environments, and lower traffic exposure appear to support physical activity across early to middle childhood. Urban planning and housing policies should prioritise child-friendly design features, such as access to play space, nature, and low traffic exposure, to promote opportunities for physical activity from early life.

Keywords: movement behaviour, built environment, neighbourhood, physical activity, children, accelerometry

## 1. Introduction

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Being physically active during childhood is vital for healthy growth and development. Regular physical activity in young children is associated with motor, cognitive and psychosocial development, cardio-respiratory and bone health, and healthy weight status (Carson et al., 2017; Pate et al., 2019; Timmons et al., 2012; Veldman et al., 2021). The 24-hour Movement Guidelines for the Early Years and for Children and Adolescents, promoted by many countries and the World Health Organization, state that preschool-aged (2-5 years) children should spend at least three hours in a variety of physical activities per day, including at least one hour in energetic play (moderate-to-vigorous physical activity), and that older (5-17 years) children achieve at least 60 minutes of energetic play per day (World Health Organization, 2019, 2020). Yet only about a quarter of children achieve recommended physical activity levels (Aubert et al., 2018).

Physical activity is dependent on multiple levels of influence from individual child and family-level factors to the broader physical and policy environment, which shape opportunities to be active (Sallis et al., 2006). Evidence from systematic reviews shows that the built environment plays a key role in determining the physical activity levels of children, although this may differ by child age, developmental stage and geographic location. For example, higher street connectivity tends to be positively associated with physical activity in older children and adolescents who have increasing independent mobility, as it provides more direct links to destinations, making neighbourhoods more walkable (Smith et al., 2022). However, the presence of cul-de-sacs, which reflect lower street connectivity, is associated with more outdoor play and physical activity in younger children with little to no independent mobility, as these environments are close to home and considered safer from traffic (Crawford et al., 2010; Ortegon-Sanchez et al., 2021). Similarly, presence of parks and playgrounds and a home yard supports outdoor free play, which is an important source of physical activity in preschoolers (Carlin et al., 2017; Gemmell et al., 2022; Robinson, Dhamrait, et al., 2024; Sheldrick et al., 2019).

53 The cross-sectional nature of studies to date limits the ability to draw conclusions on causal  
54 relationships between the built environment and young children's physical activity. Longitudinal  
55 studies are required to determine which attributes of the built environment support physical activity  
56 particularly during early to middle childhood. Most longitudinal studies of the neighbourhood  
57 environment and children's physical activity have been conducted in older school-aged children and  
58 adolescents (Berger et al., 2019; Carver et al., 2023; Crawford et al., 2010). A systematic review and  
59 meta-analysis of the relationship between the built environment and energetic play in children and  
60 adolescents found that neighbourhoods designed to promote play and walking were unexpectedly  
61 negatively associated with energetic play in 9 year-olds whereas positively associated with energetic  
62 play in 15 year-olds (McGrath et al., 2015). These findings further highlight that the relationships  
63 between the built environment and children's physical activity may be age-specific, with previous  
64 longitudinal research suggesting that the physical neighbourhood environment is relatively less  
65 important during early compared to late childhood (Crawford et al., 2010).

66

67 To date, only a handful of longitudinal studies investigating the relationship between the  
68 neighbourhood environment and young children's physical activity behaviour have been undertaken.  
69 For example, in a US study of 19,000 kindergarten children, parents who perceived their  
70 neighbourhoods to be less safe participated in less physical activity, which was consistent across all  
71 ages, although the magnitude was much weaker in longitudinal models (Datar et al., 2013). An  
72 Australian study of 4-5 year-old children who were followed up every two years until 12-13 years of  
73 age, found that an increase in neighbourhood green space was associated with increased parent- and  
74 self-reported physical activity, but only for younger boys (Sanders et al., 2015). Moreover, a  
75 prospective study of low-income preschoolers who were followed up for 3 years found that  
76 objectively-measured yard size was associated with weekly device-measured energetic play at each  
77 timepoint (Miller et al., 2020). Despite these findings, these studies were limited by the use of parent-  
78 report energetic play and parent perceptions of the built environment (Datar et al., 2013; Miller et al.,  
79 2020). Longitudinal studies using rigorous methods for processing device-based data to classify  
80 movement behaviours in young children are needed (Ahmadi & Trost, 2022).

81

82 Navigating the available evidence is further complicated due to variation in the different methods used  
83 to create measures of the built environment (Ortegon-Sanchez et al., 2021; Sterdt et al., 2014). While  
84 it is important to measure the physical environment objectively, a person's experience and perceptions  
85 of their environment should also be considered (Ortegon-Sanchez et al., 2021). In addition, measures  
86 of the neighbourhood environment are highly interdependent and also specific to a study's geographic  
87 location. To address this, studies in older school-aged children have determined neighbourhood  
88 'typologies', which consider cluster-based patterns in the built environment rather than examining  
89 features in isolation (Caetano et al., 2021; Kurka et al., 2015; Timperio et al., 2017). Yet, to our  
90 knowledge, no studies in young children have included both parent-perceived and objective measures  
91 of the physical environment to develop data-driven typologies of the neighbourhood and to examine  
92 the relationships with physical activity behaviour across early to middle childhood. Thus, this study  
93 examined the longitudinal association between neighbourhood typologies, developed through latent  
94 profile analysis using objective and perceived measures of the physical environment, and device-  
95 based physical activity behaviour in children aged two to ten years.

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## 2. Methods

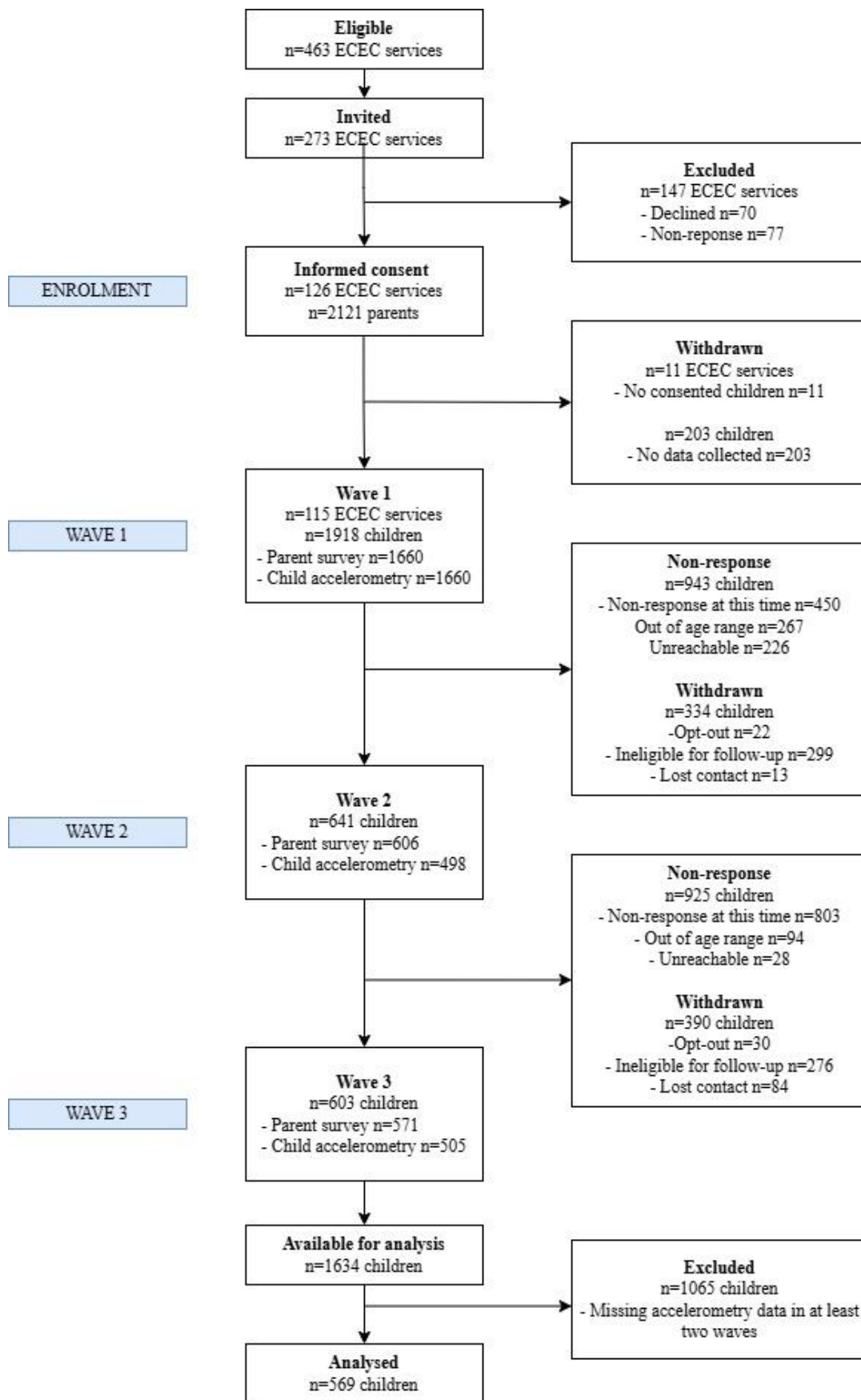
### 2.1 Study Population

99 Data from the PLAYCE (Play Spaces and Environments for Children's Physical Activity) cohort study  
100 were used in this study. PLAYCE is an observational prospective study investigating the influence of  
101 the childcare, home and neighbourhood environment on children's movement behaviours, health and  
102 development (Christian et al., 2016; Christian, 2024). Children were recruited from randomly sampled  
103 Early Childhood Education Centres (ECECs) within the Perth and Peel metropolitan area in Western  
104 Australia across low, medium and high socio-economic areas (see Figure 1). Children were eligible to  
105 be part of the PLAYCE cohort if they did not have a recognised physical, emotional/behavioural or  
106 intellectual disability that would affect participation in physical activity and were not attending full-  
107 time school at wave 1. To be eligible for follow-up, children needed to be in full-time school and  
108 living in the Perth and Peel metropolitan area. Data collected over the three waves of the PLAYCE

109 cohort study were used; wave 1 (April 2015 - April 2018; n=1,918) when children were aged 2-5  
110 years, wave 2 (October 2018 - June 2021; n=641) when children were aged 5-7 years, and wave 3  
111 (July 2021 - December 2023; n=603) when aged 8-10 years. Children were included in analyses if  
112 they had valid sociodemographic and physical environment data in wave 1 (n=1,634), and had device-  
113 measured physical activity data for at least two waves (n=569): including wave 1 and 2 only (n=128),  
114 wave 1 and 3 only (n=169), wave 2 and 3 only (n=64) and all three waves (n=208). Ethics approval  
115 was granted by The University of Western Australia Human Research Ethics Committee  
116 (2020/ET000353). A STROBE checklist is provided in Supplementary File 1.

117

119 **Figure 1:** PLAYCE cohort participant profile across waves 1, 2, and 3



120

## 121 **2.2 Device-measured physical activity**

122 Children's physical activity was measured at each wave using ActiGraph GT3X+ accelerometers  
123 (ActiGraph Corporation, Pensacola, FL USA) worn on the hip during waking hours for seven  
124 consecutive days. Raw accelerometer data (30 Hz) were processed using a random forest machine  
125 learning model for preschool-aged children developed by Ahmadi and colleagues (2020)  
126 to estimate daily time spent sedentary or doing different activities, including light intensity activities  
127 and games (e.g. slow walking, standing, standing arts and crafts), walking, running, and other  
128 moderate-to-vigorous activities and games. Daily 'energetic play' (moderate-to-vigorous intensity  
129 physical activity) was calculated as the sum of minutes of walking, running, and other moderate-to-  
130 vigorous activities and games. Daily total physical activity was calculated as the sum of minutes of  
131 light intensity activities and games, and energetic play. Sedentary time was calculated as total wear  
132 time minus total physical activity. Non-wear periods were identified by summing the time periods of  
133 at least 30 consecutive minutes during which the standard deviation of the accelerometer signal vector  
134 magnitude was <13 mg (Ahmadi et al., 2020). Children were included in the analysis if they had four  
135 or more valid accelerometer wear day (monitoring days), including a minimum of one valid weekend  
136 day. Days were considered valid if wear time was  $\geq 480$  minutes per day.

137

## 138 **2.3 Home and neighbourhood physical environment profiles**

139 Latent profile analysis was performed previously using LatentGold v6 (Innovations, 2019). Detailed  
140 methods and results from the latent profile analysis have been described in detail elsewhere (Christian  
141 et al., 2025). Only wave 1 neighbourhood physical environment profiles were included as previous  
142 research using PLAYCE cohort data identified minimal changes to built environment attributes across  
143 waves (Robinson, Boruff, et al., 2024). Objective measures of the neighbourhood physical  
144 environment were based on a 1600m road network area around participants' residential address.  
145 Parent perceptions of the neighbourhood environment were measured using a modified version of the  
146 Neighbourhood Environment Walkability Scale for Youth (NEWS-Y) (Rosenberg et al., 2009). A total  
147 of 17 objectively measured and parent perceived physical environment variables were standardised  
148 using z-scores and used for analysis. Characteristics of the profiles were considered to determine

149 whether profiles were qualitatively and quantitatively distinguishable and made conceptual sense  
 150 within the Perth and Peel (Western Australia) metropolitan geographic context. The optimum number  
 151 of profiles was found to be six, and labelled as ‘no blue space’, ‘higher public transport and  
 152 destinations mix’, ‘higher blue space access’, ‘connected residential’, ‘established’ and ‘semi-rural’  
 153 (Table 1). Full details of how these variables were calculated, as well as characteristics of the profiles,  
 154 have been published previously (Christian et al., 2025).

155

156 Table 1: Overview of PLAYCE cohort home and neighbourhood physical environment latent profiles

<b>Profile number &amp; name</b>	<b>Description</b>
1. No blue space	No blue space access, average across other physical environment features
2. Higher public transport and destination mix	High public transport access and mix of destinations
3. Higher blue space	High blue space access
4. Connected residential	Small yards with the least vegetation, highest street connectivity, low traffic exposure
5. Established	Large yards, high public transport access, high residential density
6. Semi-rural	Urban fringe, low residential density, low public transport access, low access to services

157

## 158 **2.4 Statistical analysis**

159 The characteristics of the cohort at wave 1 were analysed descriptively. To assess longitudinal  
 160 associations, linear mixed effects models with a random intercept of child were used to examine  
 161 associations between child physical activity outcomes and age by neighbourhood physical  
 162 environment latent profiles at wave 1. Nonlinear effects of age were tested using restricted cubic  
 163 splines with four knots. A series of nested models was compared using likelihood ratio tests to  
 164 determine the optimal model (linear vs. nonlinear) and whether to include interaction terms between  
 165 child age and neighbourhood physical environment profiles and child sex and neighbourhood physical  
 166 environment profiles. The mixed effects modelling accommodated incomplete physical activity data  
 167 across waves by utilising all available observations for each participant, allowing children with data at

168 two or more time points to contribute to the analyses. All models were adjusted for child sex, parent  
169 education, accelerometer wear time, and identified a priori as potential confounders of children's  
170 physical activity behaviours. The neighbourhood physical environment profile 'higher public  
171 transport and destinations mix' was selected as the reference profile for the linear mixed effects  
172 models, as at wave 1 it was the profile with the lowest average daily minutes of total physical activity  
173 (Christian et al., 2025). Model results are presented as beta ( $\beta$ ) coefficients, which represent estimated  
174 differences in mean responses between profiles, with 95% confidence intervals and corresponding p-  
175 values. All analyses were performed using R version 4.1.3 (R Core Team, 2024).

176

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### 3. Results

#### 3.1 Participants characteristics

179 A total of 569 children (50.3% girls) with a mean age of 3.2 years at wave 1 matched the data  
180 inclusion criteria (a neighbourhood physical environment latent profile and sociodemographic  
181 characteristics at wave 1 and valid accelerometer data for at least two of the three waves) (Table 2). At  
182 wave 1, average daily total physical activity was 376.8 minutes ( $\pm$  SD 51.9), energetic play was 39.3  
183 minutes ( $\pm$  SD 13.4) and sedentary time was 289.0 minutes ( $\pm$  SD 61.2). At wave 2, average daily  
184 total physical activity was 433.8 ( $\pm$  SD 90.4), energetic play was 60.3 ( $\pm$  SD 21.3) and sedentary time  
185 was 452.5 minutes ( $\pm$  SD 163.8). At wave 3, average daily total physical activity was 381.7 ( $\pm$  SD  
186 69.3), energetic play was 67.4 ( $\pm$  SD 33.4) and sedentary time was 457.1 minutes ( $\pm$  SD 82.0). Full  
187 details of children's movement behaviours across waves one to two of the PLAYCE cohort have been  
188 published previously (Christian et al., 2024).

189

190

191 Table 2: Sample characteristics at wave 1 (N=569)

<b>Sample Characteristic</b>	<b>N (%) or Mean <math>\pm</math> SD</b>
Child Age (years)	3.23 $\pm$ 0.70
Girl	286 (50.3)
Parent education	
Secondary school	63 (11.1)
Trade or diploma	135 (23.7)
Tertiary degree	371 (65.2)
Home & neighbourhood physical environment profile	
No blue space	153 (26.9)
Higher public transport & destination mix	152 (26.7)
Higher blue space	111 (19.5)
Connected residential	103 (18.1)
Established	27 (4.7)
Semi-rural	23 (4.0)
Total physical activity (mins/day)*	376.83 $\pm$ 51.86
Light intensity activities and games (mins/day)	337.51 $\pm$ 48.13
Energetic play (mins/day)	39.32 $\pm$ 13.35
Walking (mins/day)	17.94 $\pm$ 8.05
Running (mins/day)	4.16 $\pm$ 2.83
Other moderate to vigorous activities and games (mins/day)	17.21 $\pm$ 9.71
Sedentary (mins/day)	288.96 $\pm$ 61.18
Total wear time (mins/day)	665.79 $\pm$ 61.84

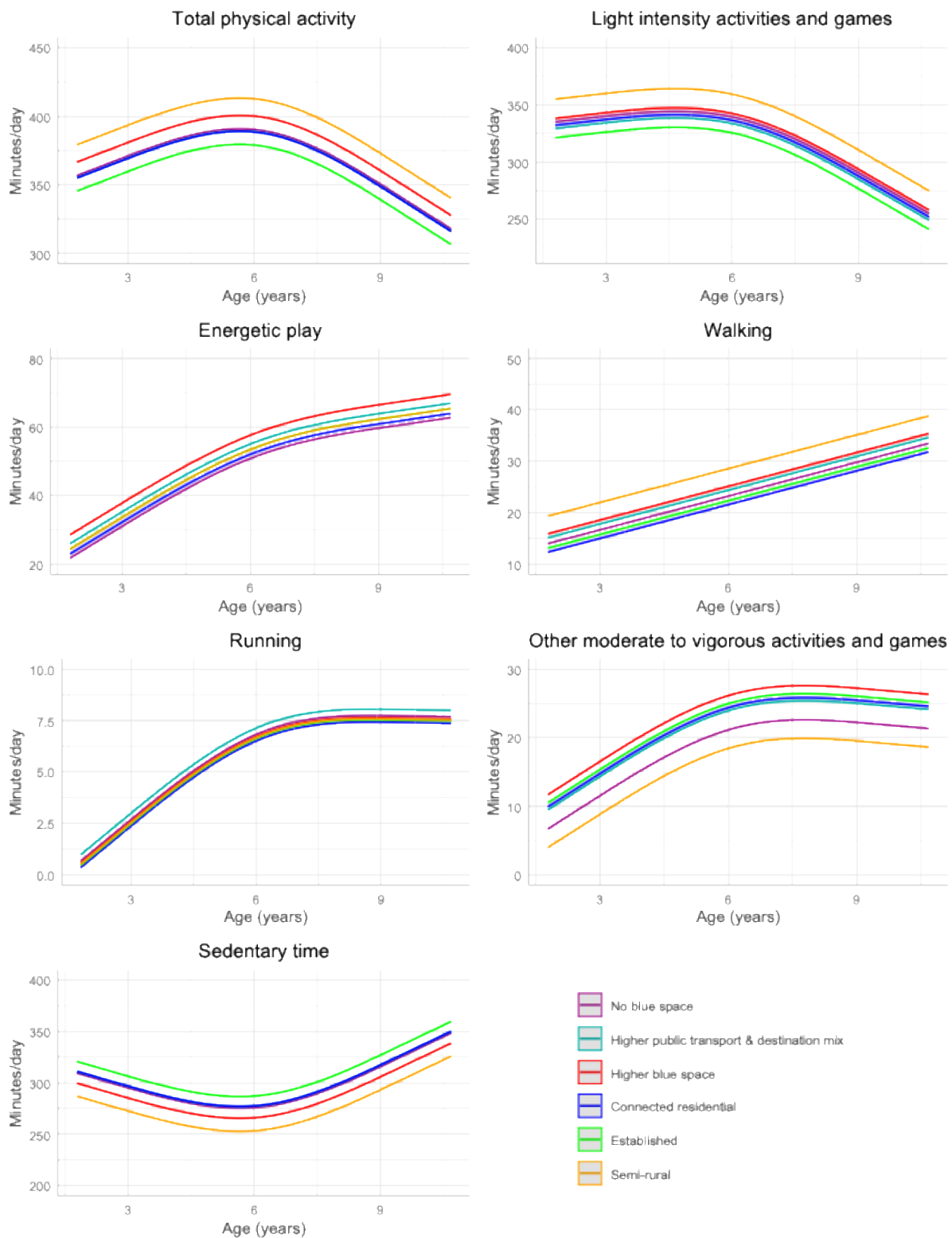
\* Note only n=505 had actigraphy data available for wave 1.

192

193 **3.2 Change in physical activity behaviours by age and neighbourhood physical environment**  
194 **profile**

195 There were notable changes in children’s mean daily minutes of physical activity behaviours over  
196 time, with consistent increases in both energetic play and walking from age two to ten years (Figure  
197 2). Similarly, running and moderate to vigorous activities and games, increased from age two to  
198 seven, then remained relatively stable. In contrast, total daily physical activity and light-intensity  
199 activities and games slightly increased from age two to six, followed by a steady decline from six to  
200 ten years. Sedentary time decreased from ages two to six and then increased between ages six to ten to  
201 levels higher than at age two. Overall, the mean time spent in all physical activity behaviours, except  
202 for walking, demonstrated a non-linear relationship with age for all neighbourhood physical  
203 environment profiles.

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206

207 **Figure 2:** Child physical activity behaviours by age and neighbourhood physical environment profile.

208 *Figure notes: Figures show estimated means from linear mixed models adjusted for child sex, parent*

209 *education and accelerometer wear time. Energetic play = sum of walking, running, and other*

210 *moderate-to-vigorous activities and games. Total physical activity = sum of light intensity activities*

211 *and games and energetic play. Sedentary time = total wear time minus total physical activity.*

212 **3.3 Longitudinal associations between home and neighbourhood physical environment profiles**  
213 **and young children's physical activity behaviours**

214 There was no significant home and neighbourhood physical environment profile by child age or sex  
215 interactions across the physical activity behaviour variables, indicating that the differences in profiles  
216 were consistent across ages and sexes. After adjustment for socio-demographic factors, children living  
217 in the 'semi-rural' profile had higher mean levels of daily total physical activity ( $\beta = 25.1$  more minutes;  
218 95% CI: 4.2, 46.1), light intensity activities and games ( $\beta = 26.4$  more minutes; 95% CI: 7.0, 45.9), and  
219 walking ( $\beta = 4.5$  more minutes; 95% CI: 0.99, 8.1), compared to children in the 'higher public transport  
220 and destinations mix' profile (Table 3).

221  
222 Children living in the 'no blue space' profile had lower levels of daily energetic play ( $\beta = 4.6$  less  
223 minutes; 95% CI: 0.8-8.4) than children living in the 'higher public transport and destinations mix'  
224 profile. Similarly, children living in the 'connected residential' profile had lower levels of daily walking  
225 ( $\beta = 2.9$  less minutes; 95% CI: 0.7, 5.0), compared to children living in the 'higher public transport and  
226 destinations mix' profile.

227  
228 Post hoc pairwise comparisons of home and neighbourhood physical environment profiles (based on  
229 the final mixed-effects model) indicated that children living in the 'semi-rural' profile had higher levels  
230 of walking across all age ranges compared with those in all other profiles (see Supplementary Table 2).  
231 Children living in the 'semi-rural' profile also had higher levels of total daily physical activity and light  
232 intensity activities and games across all age ranges compared with those in all other profiles except the  
233 'higher blue space' profile. The largest difference was observed between the 'semi-rural' and  
234 'established' profiles, with children in the 'semi-rural' profile having on average 36.7 minutes more of  
235 total physical activity per day (95% CI: 9.4, 63.9), and 36.2 minutes more of light intensity activities  
236 and games (95% CI: 10.9, 61.5). In addition, children living in the 'higher blue space' profile did more  
237 daily total physical activity compared with those living in the 'established' profile ( $\beta = 22.3$  more  
238 minutes; 95% CI: 1.0, 43.5).

239

240

**Table 3: Longitudinal associations between neighbourhood physical environment profiles and children's daily minutes of physical activity behaviours**

Home & neighbourhood profile (continuous %)	Total physical activity (mins/day)	Light intensity activities and games (mins/day)	Energetic play (mins/day)	Walking (mins/day)	Running (mins/day)	Other moderate to vigorous activities and games (mins/day)	Sedentary time (mins/day)
	$\beta$ (95% CI)	$\beta$ (95% CI)	$\beta$ (95% CI)	$\beta$ (95% CI)	$\beta$ (95% CI)	$\beta$ (95% CI)	$\beta$ (95% CI)
No blue space	0.51 (-10.86, 11.88)	5.08 (-5.47, 15.63)	<b>-4.60 (-8.36, -0.84)</b>	-1.54 (-3.47, 0.39)	-0.25 (-0.99, 0.49)	-2.78 (-6.17, 0.60)	-0.51 (-11.88, 10.86)
Higher public transport & destination mix	reference	reference	reference	reference	reference	reference	reference
Higher blue space	10.73 (-1.52, 22.99)	8.47 (-2.90, 19.84)	2.28 (-1.78, 6.33)	0.52 (-1.56, 2.59)	-0.48 (-1.28, 0.32)	2.25 (-1.41, 5.90)	-10.73 (-22.99, 1.52)
Connected residential	1.540 (-11.09, 14.18)	4.55 (-7.18, 16.28)	-2.97 (-7.14, 1.21)	<b>-2.88 (-5.02, -0.74)</b>	-0.55 (-1.38, 0.28)	0.49 (-3.27, 4.24)	-1.54 (-14.18, 11.09)
Established	-11.54 (-32.13, 9.06)	-9.78 (-28.90, 9.34)	-1.78 (-8.59, 5.02)	-2.08 (-5.57, 1.41)	-0.41 (-1.76, 0.94)	0.78 (-5.34, 6.90)	11.54 (-9.06, 32.13)
Semi-rural	<b>25.11 (4.15, 46.07)</b>	<b>26.44 (6.97, 45.92)</b>	-1.32 (-8.23, 5.60)	<b>4.54 (0.99, 8.09)</b>	-0.49 (-1.87, 0.90)	-5.5 (-11.71, 0.70)	<b>-25.11 (-46.07, -4.15)</b>

241

Linear mixed effect models adjusting for child age and sex, wave 1 parent education and accelerometer wear time. Home and neighbourhood profiles were included as continuous exposure variables with  $\beta$  being

242

the estimated difference in mean physical activity behaviour time between home & neighbourhood profiles and the 'Higher public transport & destination mix' reference profile.  $P < 0.05$  bolded. Sedentary time

243

results are the same as total physical activity, as accelerometer wear time was adjusted for in all models (i.e., sedentary time + total physical activity = wear time).

244

#### 4. Discussion

245  
246 This longitudinal study examined associations between home and neighbourhood physical environment  
247 profiles and physical activity behaviour from early to middle childhood. For all six home and  
248 neighbourhood physical environment profiles, there was a non-linear relationship with all physical activity  
249 behaviours (except walking) across the ages of two to ten years old. Compared to the home and  
250 neighbourhood profile with the lowest levels of physical activity ('higher public transport and destination  
251 mix'), children living in the 'semi-rural' neighbourhood profile did significantly more daily minutes of total  
252 physical activity, walking, and light intensity activities and games, while children living in the 'no blue  
253 space' and 'connected residential' neighbourhood profiles did significantly less daily minutes of energetic  
254 play and walking, respectively.

255  
256 Despite declines in children's total physical activity levels after age six, those living in 'semi-rural'  
257 neighbourhoods consistently engaged in more physical activity across early to middle childhood.  
258 Specifically, children in these neighbourhoods spent significantly more time walking (4 to 7 minutes per  
259 day) than children in all other neighbourhood profiles, and more time in light-intensity activities and games  
260 (21 to 36 minutes per day) as well as more physical activity in total (24 to 37 minutes per day) than all other  
261 profiles except for the 'higher blue space' profile. The 'semi-rural' neighbourhoods were characterised by  
262 lower residential density, larger home yards, high neighbourhood greenness, low street connectivity, and  
263 limited public transport and destination accessibility. Children in these environments may have benefited  
264 from greater access to play spaces and nature environments, supporting light-intensity play despite limited  
265 access to public transport and local destinations and more sedentary car dependency to get to places.

266  
267 In stark contrast with children living in 'semi-rural' neighbourhoods, those who lived in the 'established'  
268 neighbourhoods spent 37 fewer minutes per day being physically active, mostly due to lower engagement  
269 in light-intensity activities and games. These neighbourhoods had high residential density and more roads  
270 with higher traffic exposure, but had access to relatively large home yards and good vegetation, public

271 transport and a mixture of local destinations (e.g. post office, bank, dentist, library, childcare). The findings  
272 suggest that higher density and traffic exposure may limit children's opportunities for outdoor play, even  
273 when amenities and green space are present. Children who lived in the 'higher blue space' neighbourhood  
274 showed intermediate levels of light-intensity activity and physical activity in total, though not significantly  
275 different from either the 'semi-rural' or the 'higher public transport and destinations mix' profile. This  
276 suggests that neighbourhoods with high levels of blue space (e.g. beaches, riverways, canals), despite  
277 performing moderately on all other physical environment features, may be supportive of physical activity  
278 in young children.

279  
280 Further supporting these findings, children living in neighbourhoods with few natural spaces, characterised  
281 by 'no blue space' and those predominantly in 'connected residential', spent around five minutes less per day  
282 in energetic play and walking. These neighbourhoods had limited yard space, lower greenness, minimal  
283 blue space, and relatively lower public transport and destination access. This suggests that reduced access  
284 to nature, play spaces, public transport and destinations creates fewer opportunities for children's physical  
285 activity.

286  
287 Overall, the profiles suggest that lower residential density, larger home yards, greater access to green and  
288 blue spaces, and lower traffic exposure are consistently associated with high levels of physical activity in  
289 early to middle childhood, especially for their participation in light-intensity activities and games. This is  
290 consistent with previous studies. Research with six- to 12-year-olds demonstrated that higher residential  
291 density was associated with greater declines in energetic play over a two-year follow-up, potentially due to  
292 these high density neighbourhoods lacking play spaces as more lands were allocated to housing (Carver et  
293 al., 2023). Similarly, a large longitudinal study across three European countries identified that access to  
294 public open space and lower residential density were positively associated with device-measured physical  
295 activity, particularly light-intensity activity in children aged three to 15 years (Buck et al., 2019). Studies  
296 from the US and Australia have also shown neighbourhood profiles featuring higher park or playground

297 access were associated with greater energetic play among children aged 2 to 5 and 6 to 12 years (Bai et al.,  
298 2024; Kurka et al., 2015). Access to blue space has been suggested to provide children with opportunities  
299 for light-intensity activities such as slow walking or standing (George et al., 2024; Pasanen et al., 2019).  
300 Moreover, study examining neighbourhood profiles and obesity suggested that neighbourhoods with lower  
301 traffic safety were the most obesogenic for children aged 8 to 10, regardless of having good access to parks  
302 and high walkability, as traffic unsafety discourages outdoor play and active transport (Barnett et al., 2021).

303

304 These findings have important implications for policy and planning. While findings suggest  
305 neighbourhoods located on the urban fringe, where it is possible to have larger backyards and greater access  
306 to natural green spaces, support children from early to middle childhood to engage in more daily active  
307 play, they are not sustainable for managing the balance between sustainable urban design and population  
308 growth. However, the findings highlight the need for preserving natural green spaces for generations to  
309 come, rather than clearing them to increase housing density. Moreover, where families are unable to afford  
310 a home with a large backyard and access to natural spaces is lacking, greater urban planning priorities  
311 should include providing access to child-friendly, high quality play spaces close to home, and promoting  
312 greening initiatives that create nature exposure for children. Traffic safety should also be prioritised, given  
313 that the established neighbourhoods, with big home yards and yet more busy roads, were associated with  
314 less time spent on physical activity in children. It is therefore recommended for future policy and planning  
315 to consider traffic safety as an important consideration for children's outdoor play and mobility. The  
316 consistency of associations across early to middle childhood suggests that urban environments play a lasting  
317 role in children's movement behaviours. And investments in supportive environments may have durable  
318 benefits, whereas failure to address barriers may reinforce reduced physical activity over time.

319

#### 320 **4.1 Study strengths and limitations**

321 The longitudinal design, spanning early to middle childhood with a large sample and repeated measures  
322 from ages two to ten are study strength. The application of machine learning derived physical activity

323 classification models to process the accelerometry data enabled more accurate differentiation of activity  
324 types than traditional cut-point methods, which tend to underestimate light intensity physical activity time  
325 and overestimate energetic play time (Ahmadi et al., 2020; Ahmadi & Trost, 2022). Additionally, the latent  
326 profile approach captured complex combinations of neighbourhood characteristics that better represented  
327 real-world environments, providing a useful step that can inform further research to unpack the direct and  
328 indirect impacts of neighbourhood environments on children's physical activity behaviour.

329

330 This study was conducted in a single geographical area, potentially limiting generalisability of the findings  
331 to cities with different geographical profiles (e.g., high-density cities) and cultural contexts (e.g., not  
332 Western educational settings). Second, we included 17 objectively measured and parent-perceived physical  
333 environment factors, but we did not capture additional factors that may influence children's physical  
334 activity. This includes the availability of other child-relevant facilities such as schools, play equipment,  
335 playgrounds, and perceived quality of green spaces, which is suggested to influence actual usage of green  
336 spaces more than objective measures (Bringolf-Isler et al., 2019). While physical activity was measured  
337 using devices, wear time was somewhat limited (approximately 11 hours per day), given the devices were  
338 not waterproof. This limited the detection of water-based activities, which are important sources of physical  
339 activity for Western Australian children, as swimming remains the most popular sport for children aged 0-  
340 11, with an estimated 25% participation rate (2025). Future research should integrate a broader range of  
341 objective and perceived child play-relevant destinations and facilities to provide a more comprehensive  
342 understanding of the physical environment in relation to children's physical activity across childhood.  
343 Additionally, investigating physical activity by time of day (school time, out-of-school time), context or  
344 setting (school, playground, aquatic), would clarify the role and contribution of different environmental  
345 contexts on children's movement behaviours across key settings in which children spend their time.

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## 5. Conclusion

This longitudinal study demonstrates that neighbourhood physical environment profiles featuring access to home yards, natural green and blue spaces, and reduced traffic exposure are consistently associated with higher physical activity levels from early to middle childhood. The significant and sustained benefits highlight the enduring role of neighbourhood infrastructure in shaping children’s daily movement behaviours. These findings provide locally relevant evidence for urban planning and policy decisions aimed at promoting children's physical activity. As cities grow and densify, priorities should be given to preserving access to natural spaces, improving the availability of play spaces, and enhancing traffic safety. Future work should continue to investigate activity-supportive neighbourhood environments across urban contexts and integrate broader physical environment measures.

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392

### 393 **Author contributions**

394 MZ: writing – original draft, writing – review and editing

395 CB: formal analysis, writing – original draft, writing – review and editing

396 ST: methodology, data curation

397 JS: methodology, writing – review and editing

398 KM: formal analysis, writing – review and editing

399 BB: methodology, writing – review and editing

400 GS: writing – review and editing, funding acquisition

401 HC: conceptualisation, methodology, investigation, writing – original draft, writing – review and editing,  
402 supervision, project administration, funding acquisition.

403

### 404 **Ethical considerations**

405 Ethics approval was granted by The University of Western Australia Human Research Ethics Committee  
406 (RA/4/1/ 7417 and 2020/ET000353). Parents provided written informed consent for themselves and their  
407 child to participate.

408

### 409 **Data availability statement**

410 The datasets used during the current study are available through application to the PLAYCE study.

411

412 **Competing interests statement**

413 The authors declare no competing interests.

414

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	Item No	Recommendation	Page No
Title and abstract	1	(a) Indicate the study's design with a commonly used term in the title or the abstract	1
		(b) Provide in the abstract an informative and balanced summary of what was done and what was found	1
<b>Introduction</b>			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	2-4
Objectives	3	State specific objectives, including any prespecified hypotheses	4
<b>Methods</b>			
Study design	4	Present key elements of study design early in the paper	4-5
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	4-5
Participants	6	(a) Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up	4-5
		(b) For matched studies, give matching criteria and number of exposed and unexposed	N/A
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	7-8
Data sources/ measurement	8	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	7-8
Bias	9	Describe any efforts to address potential sources of bias	4-5
Study size	10	Explain how the study size was arrived at	4-5
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	8-9
Statistical methods	12	(a) Describe all statistical methods, including those used to control for confounding	8-9
		(b) Describe any methods used to examine subgroups and interactions	8-9
		Explain how missing data were addressed	8-9
		(d) If applicable, explain how loss to follow-up was addressed	N/A
		Describe any sensitivity analyses	N/A
<b>Results</b>			
Participants	13	(a) Report numbers of individuals at each stage of study— eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	6
		(b) Give reasons for non-participation at each stage	6

		Consider use of a flow diagram	6
Descriptive data	14	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	9-10
		(b) Indicate number of participants with missing data for each variable of interest	5
		Summarise follow-up time (eg, average and total amount)	5
Outcome data	15	Report numbers of outcome events or summary measures over time	9-12
Main results	16	(a) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	13-14
		(b) Report category boundaries when continuous variables were categorized	N/A
		If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	N/A
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	N/A
Discussion			
Key results	18	Summarise key results with reference to study objectives	15-18
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	18-19
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	19
Generalisability	21	Discuss the generalisability (external validity) of the study results	18-19
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	20-21

**Supplementary Table 2: All pairwise comparisons between neighbourhood physical environment profile and child physical activity**

**behaviours**

Profile comparisons	Total physical activity (mins/day)	Light intensity activities and games (mins/day)	Energetic play (mins/day)	Walking (mins/day)	Running (mins/day)	Other moderate to vigorous activities and games (mins/day)	Sedentary time (mins/day)
	$\beta$ (95% CI)	$\beta$ (95% CI)	$\beta$ (95% CI)	$\beta$ (95% CI)	$\beta$ (95% CI)	$\beta$ (95% CI)	$\beta$ (95% CI)
2 vs 1	-0.51 (-11.88, 10.86)	-5.08 (-15.63, 5.47)	<b>4.60 (0.84, 8.36)</b>	1.54 (-0.39, 3.47)	0.25 (-0.49, 0.99)	2.78 (-0.60, 6.17)	0.51 (-10.86, 11.88)
3 vs 1	10.22 (-1.95, 22.39)	3.39 (-7.90, 14.68)	<b>6.88 (2.86, 10.9)</b>	2.06 (0.00, 4.12)	-0.23 (-1.03, 0.57)	<b>5.03 (1.41, 8.65)</b>	-10.22 (-22.39, 1.95)
4 vs 1	1.03 (-11.55, 13.61)	-0.53 (-12.22, 11.15)	1.63 (-2.52, 5.78)	-1.34 (-3.47, 0.79)	-0.30 (-1.13, 0.52)	3.27 (-0.46, 7.00)	-1.03 (-13.61, 11.55)
5 vs 1	-12.05 (-32.75, 8.65)	-14.86 (-34.08, 4.35)	2.82 (-4.02, 9.65)	-0.54 (-4.05, 2.97)	-0.16 (-1.52, 1.20)	3.56 (-2.59, 9.71)	12.05 (-8.65, 32.75)
6 vs 1	<b>24.60 (3.68, 45.52)</b>	<b>21.36 (1.92, 40.80)</b>	3.28 (-3.61, 10.18)	<b>6.08 (2.54, 9.62)</b>	-0.23 (-1.62, 1.15)	-2.72 (-8.91, 3.47)	<b>-24.60 (-45.52, -3.68)</b>
3 vs 2	10.73 (-1.52, 22.99)	8.47 (-2.90, 19.84)	2.28 (-1.78, 6.33)	0.52 (-1.56, 2.59)	-0.48 (-1.28, 0.32)	2.25 (-1.41, 5.90)	-10.73 (-22.99, 1.52)
4 vs 2	1.54 (-11.09, 14.18)	4.55 (-7.18, 16.28)	-2.97 (-7.14, 1.21)	<b>-2.88 (-5.02, -0.74)</b>	-0.55 (-1.38, 0.28)	0.49 (-3.27, 4.24)	-1.54 (-14.18, 11.09)
5 vs 2	-11.54 (-32.13, 9.06)	-9.78 (-28.90, 9.34)	-1.78 (-8.59, 5.02)	-2.08 (-5.57, 1.41)	-0.41 (-1.76, 0.94)	0.78 (-5.34, 6.90)	11.54 (-9.06, 32.13)
6 vs 2	<b>25.11 (4.15, 46.07)</b>	<b>26.44 (6.97, 45.92)</b>	-1.32 (-8.23, 5.60)	<b>4.54 (0.99, 8.09)</b>	-0.49 (-1.87, 0.90)	-5.50 (-11.71, 0.70)	<b>-25.11 (-46.07, -4.15)</b>
4 vs 3	-9.19 (-22.75, 4.37)	-3.92 (-16.50, 8.66)	<b>-5.25 (-9.73, -0.77)</b>	<b>-3.40 (-5.69, -1.10)</b>	-0.07 (-0.96, 0.81)	-1.76 (-5.79, 2.27)	9.19 (-4.37, 22.75)
5 vs 3	<b>-22.27 (-43.53, -1.01)</b>	-18.25 (-37.98, 1.48)	-4.06 (-11.09, 2.96)	-2.60 (-6.20, 1.00)	0.07 (-1.32, 1.47)	-1.47 (-7.78, 4.85)	<b>22.27 (1.01, 43.53)</b>
6 vs 3	14.38 (-7.07, 35.82)	17.97 (-1.95, 37.90)	-3.59 (-10.67, 3.48)	<b>4.02 (0.39, 7.66)</b>	-0.01 (-1.42, 1.41)	<b>-7.75 (-14.1, -1.40)</b>	-14.38 (-35.82, 7.07)
5 vs 4	-13.08 (-34.60, 8.44)	-14.33 (-34.31, 5.65)	1.18 (-5.92, 8.29)	0.80 (-2.85, 4.45)	0.15 (-1.27, 1.56)	0.29 (-6.09, 6.68)	13.08 (-8.44, 34.60)
6 vs 4	<b>23.57 (1.90, 45.24)</b>	<b>21.89 (1.76, 42.03)</b>	1.65 (-5.49, 8.80)	<b>7.42 (3.75, 11.09)</b>	0.07 (-1.36, 1.50)	-5.99 (-12.40, 0.42)	<b>-23.57 (-45.24, -1.90)</b>
6 vs 5	<b>36.65 (9.42, 63.87)</b>	<b>36.22 (10.93, 61.51)</b>	0.47 (-8.51, 9.45)	<b>6.62 (2.01, 11.23)</b>	-0.08 (-1.87, 1.72)	-6.28 (-14.35, 1.78)	<b>-36.65 (-63.87, -9.42)</b>

1= No blue space; 2= Higher public transport and destination mix; 3= Higher blue space; 4= Connected residential; 5= Established; 6= Semi-rural  
 Linear mixed effect models adjusting for child age and sex, wave 1 parent education and accelerometer wear time. Home and neighbourhood profiles were included as continuous exposure variables with  $\beta$  being the estimated difference in mean physical activity behaviour time between home & neighbourhood profiles and the 'Higher public transport & destination mix' as the reference group. P<0.05 bolded. Sedentary time results are the same as total physical activity as accelerometer wear time was adjusted for in all models (i.e., sedentary time + total physical activity = wear time).