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Review

Health impact assessment of active transportation: A systematic review

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ABSTRACT

Objective. Walking and cycling for transportation (i.e. active transportation, AT), provide substantial health benefits from increased physical activity (PA). However, risks of injury from exposure to motorized traffic and their emissions (i.e. air pollution) exist. The objective was to systematically review studies conducting health impact assessment (HIA) of a mode shift to AT on grounds of associated health benefits and risks.

Methods. Systematic database searches of MEDLINE, Web of Science and Transportation Research International Documentation were performed by two independent researchers, augmented by bibliographic review, internet searches and expert consultation to identify peer-reviewed studies from inception to December 2014.

Results. Thirty studies were included, originating predominantly from Europe, but also the United States, Australia and New Zealand. They compromised of mostly HIA approaches of comparative risk assessment and cost–benefit analysis. Estimated health benefit–risk or benefit–cost ratios of a mode shift to AT ranged between −2 and 360 (median = 9). Effects of increased PA contributed the most to estimated health benefits, which strongly outweighed detrimental effects of traffic incidents and air pollution exposure on health.

Conclusion. Despite different HIA methodologies being applied with distinctive assumptions on key parameters, AT can provide substantial net health benefits, irrespective of geographical context.

Contents

Abbreviations: AT, active transportation; CVD, cardiovascular disease; DALYs, disability-adjusted life years; DRF, dose–response function; HEAT, Health Economic Assessment Tool; HIA, health impact assessment; PA, physical activity; $PM_{2.5}$, particulate matter less than 2.5 μm; RR, relative risk; TRAP, traffic-related air pollution; WHO, World Health Organization.

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Introduction

Contemporary car-ownership, and the vast network of roadway systems to accommodate it, adversely impact public health through environmental pathways such as air pollution, noise, greenhouse gas emissions, and traffic hazards (Haines and Dora, 2012). The convenience of motorized transportation has reduced dependence on physically-demanding travel while simultaneously increasing sedentary time spent (González-Gross and Meléndez, 2013). Today, globally, more than 30% of all adults are estimated to perform insufficient physical activity (PA) (Hallal et al., 2012). A lack of PA is associated with all-cause mortality, cardiovascular diseases (CVD), type 2 diabetes, cancer and impaired mental health (Physical Activity Guidelines Advisory Committee, 2008), and together with an energy-dense diet, the driving force of the progressing obesity epidemic (Ng et al., 2014).

The promotion of walking and cycling for transportation complemented by public transportation or any other 'active' mode, i.e. active transportation (AT), presents a promising strategy to not only address problems of urban traffic strain, environmental pollution and climate change, but also to provide substantial health benefits (de Hartog et al., 2010). Despite associated risks of exposure to traffic and to a lesser extent air pollution (de Nazelle et al., 2011), AT may overcome car dependence and increase PA levels (Lindsay et al., 2011).

In recent years, there has been growing interest in health impact assessment (HIA) as a method to estimate potential health consequences of non-healthcare interventions (Mindell et al., 2003). HIA aims at identifying the direction and magnitude of potential health impacts of these interventions in order to mitigate harms and increase health benefits (Mindell and Joffe, 2003). As until now longitudinal pre-/post-intervention studies in AT are scarce, HIA has to make do with scenarios to study what health effects would be if changes in transportation behavior took place. To our knowledge, despite evidence of AT health benefits (Cavill et al., 2008; Teschke et al., 2012; Xia et al., 2013), a systematic review quantifying health benefits and risks of AT does not yet exist. Therefore, we systematically reviewed studies conducting quantitative HIA of a mode shift to AT.

Methods

This review was performed following the PRISMA guidelines for reporting of systematic reviews (Moher et al., 2009). Systematic database searches of MEDLINE, Web of Science and Transportation Research International Documentation were conducted. Keyword combinations of "health impact assessment", "active transportation", "physical activity", "traffic incidents", "air pollution" and "noise" were used (Appendix A.1). Limits were English, Spanish, Dutch, French, or German language and abstract availability. Manual bibliographic review, internet searches and expert consultation were conducted to ensure completeness of peer-reviewed studies. Two independent researchers (NM and DR-R) performed all levels of screening and discrepancies were resolved by consensus.

Eligibility criteria

For review inclusion the study had to (1) focus on prospective or retrospective interventions in transportation, built-environment, land-use, economy, or energy that produced a mode shift between motorized transportation and AT; (2) include a quantitative HIA methodology of comparative risk assessment, cost–benefit analysis, risk assessment or benefit assessment; (3) report a quantitative change in the exposure distribution of at least one health pathway; and (4) report a quantitative change in at least one health endpoint.

Outcome measure

The benefit–risk or benefit–cost relationship of the AT mode shift was the primary outcome of this review. If not reported by the study and if possible, the benefit–risk or benefit–cost ratio was calculated based on expected change in exposure distribution of health pathways resulting from a mode shift to AT.

Data extraction and synthesis

Essential data of eligible studies were extracted into a data extraction tool for descriptive and analytic synthesis (Appendix A.2). The literature search, study selection, data extraction and synthesis were performed between February 2, 2014 and December 9, 2014.

Results

Search results

The literature search produced a list of 3594 articles. Initial title screening identified 333 candidate studies. Abstract screening identified 130 candidate studies and independent full-text reading resulted in 30 eligible studies (Fig. 1).

Study characteristics

The 30 eligible studies were published between September 2001 and January 2015 (Table 1). Interventions that produced a mode shift, and of which health impacts were estimated, included measures which make AT more attractive (e.g. bike-sharing system), or discourage private vehicle use (e.g. fuel price increase). Eighteen studies assessed health impacts of AT within Europe. One study compared London (UK) and Delhi (India). Seven studies estimated health impacts of AT in the United States. Five studies assessed health impacts in Australia and New Zealand. The studies covered a range of populations

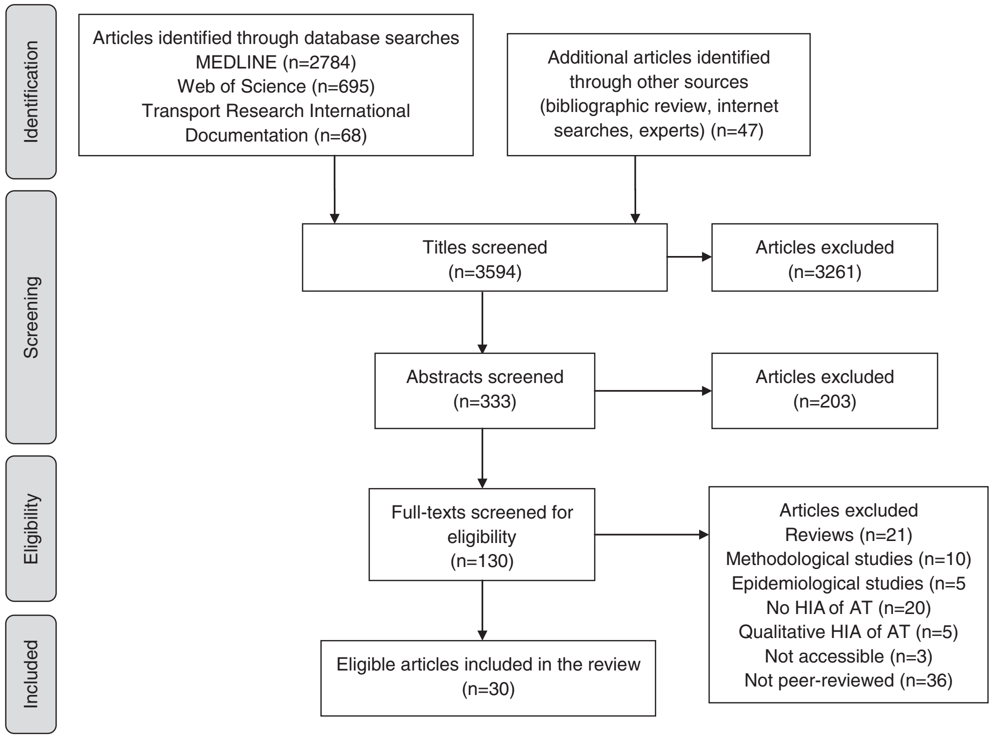

Fig. 1. Flow chart for study selection.

consisting mostly of driving-aged adults, partially stratified by age, sex, ethnicity or population density.

Twelve studies conducted comparative risk assessment, comparing estimated health benefits and risks of changed health pathway exposure distribution resulting from a mode shift to AT (Table 2). Twelve studies used cost–benefit analysis to estimate economic impacts. Of these, seven studies compared estimated benefits to intervention costs, while the other four compared savings and costs of expected health benefits and risks. Four studies were benefit assessments in which risks or costs were not considered. Two studies conducted risk assessment exclusively of traffic safety.

Physical activity

All studies, except Stipdonk and Reurings (2012) and Schepers and Heinen (2013), assessed the health impacts of increased PA resulting from a mode shift to AT. PA risk estimates for associated health outcomes used across the studies were taken predominantly from meta-analyses (Appendix B.1). The majority of studies assumed a linear association between PA and health. The World Health Organization's (WHO) Health Economic Assessment Tool (HEAT) was applied in seven studies and uses a log-linear dose–response function (DRF) between PA and all-cause mortality by applying a 22% risk reduction per 29 min of daily walking (World Health Organization, 2011), and a 28% risk reduction per 3 h of cycling per week (Andersen et al., 2000). HEAT caps a risk reduction at a threshold of 50%. Likewise, three studies used a linear DRF with either a threshold (Woodcock et al., 2009; Jarrett et al., 2012), or a square-root function for higher PA levels (Maizlish et al., 2013). Four studies modeled PA exposure with a continuous non-linear DRF with the consideration of baseline PA levels (Rabl and de Nazelle, 2012; Dhondt et al., 2013; Woodcock et al., 2013, 2014). Six studies used PA categories assigned with distinctive relative risks (RR) (Mooy and Gunning-Schepers, 2001; Sælensminde, 2004; Boarnet et al., 2008; Cobiac et al., 2009; Holm et al., 2012; Xia et al., 2015). All 28 studies obtained estimates for PA with a mode shift to AT that resulted in reductions in all-cause mortality, CVD, type 2 diabetes, weight gain, cancer, falls, or impaired mental health.

Traffic incidents

Twenty-one studies estimated health impacts of exposure to traffic with regard to fatality and injury risk, and one study with regard to the feeling-of-insecurity (Sælensminde, 2004). In all 21 studies, traffic incidents were estimated directly based on local or national statistics by including travel exposure data (Appendix B.1). The majority of studies modeled traffic incident risk linearly by mode-specific distance or time traveled. Eight studies, however, assumed non-linearity of risk by including risk components of a disproportional increase in traffic incidents ('safety in numbers'), changes in traffic volume, modal split, conflict types and kinetic energies, speed and road type traveled, as well as age and sex effects (Gotschi, 2011; Lindsay et al., 2011; Maizlish et al., 2013; Schepers and Heinen, 2013; Woodcock et al., 2013, 2014; Macmillan et al., 2014; Xia et al., 2015). Fourteen studies estimated overall increases in traffic fatalities and injuries with increased levels of AT, while six studies estimated overall decreases in fatalities and injuries. Gotschi (2011) assumed no change in absolute number of traffic fatalities.

Air pollution

Seventeen studies estimated the health impacts of air pollution exposure. Air pollution risk estimates used across the studies were taken predominantly from longitudinal studies, but also from time-series analyses (Appendix B.1). While ten studies estimated health benefits to the general population from reduced car use and associated exposure reductions, three studies estimated the active traveler's individual exposure risk. Four studies included both estimations for the benefits to the population and the risk to the active traveler. Most frequently, $PM_{2.5}$ (particulate matter less than 2.5 μm) was used as a proxy for air pollution. Other traffic-related air pollution (TRAP) components considered included ozone, carbon monoxide, or elemental carbon. All studies,

Table 1
Quantitative health impact assessment studies of a mode shift to active transportation.

Author (year)	Method	Study setting[a]	Active transportation mode shift scenarios[b]	Health pathways[c]	Health endpoints[d]
Mooy and Gunning-Schepers (2001)	BA	Netherlands; age 16–64 years; stratification by sex	Replace 100% (S1); 41% (S2) of car trips ≤10 km with bicycle	Physical activity	Ischemic heart disease mortality
Sælensminde (2004)	CBA[e]	Hokksund; Hamar; Trondheim (Norway)	Replace 15% of car trips ≤5 km with walking (1/3) and cycling (2/3) in Hokksund (S1); Hamar (S2); Trondheim (S3) by new walking and cycling infrastructure	Physical activity; [traffic incidents][f]	Health costs (NOK; insecurity, work absence, health care)
Boarnet et al. (2008)	BA	Portland (USA); population of 5,000	Predictability of walking on grounds of land-use features	Physical activity	Health costs ($US; mortality)
Cobiac et al. (2009)	CBA[e]	Australia; 5.4 million households; age ≥15 years	AT information and merchandise campaign (TravelSmart)	Physical activity	Health costs ($AUS; mortality, morbidity, health care)
Woodcock et al. (2009)	CRA	London (UK); Delhi (India); age ≥15 years	Transportation CO_2 reduction by low carbon driving (S1); AT (S2); sustainable transportation, S1 combined with S2 (S3); short distance AT (S4)	Physical activity; traffic incidents; air pollution GP	DALYs; morbidity; overweight and obesity
Guo and Gandavarapu (2010)	CBA[e]	Dane County (USA); population of 4,974; age ≥17 years	Addition of 1,220 miles of sidewalk	Physical activity	Health costs ($US; weight gain)
de Hartog et al. (2010)	CRA	Netherlands; population of 500,000; age 18–64 years; stratification by age	Replace car round-trips 7.5 km (S1); 15 km (S2) with bicycle	Physical activity; traffic incidents; air pollution AcT and [GP]	Life expectancy
Gotschi (2011)	CBA[e]	Portland (USA); population of 582,000	Infrastructure investment of 138–605 million US$ (S1–S3) to increase bicycle share of distances ≤3 miles	Physical activity; [traffic incidents]	Health costs ($US; mortality, inactivity); lives saved
Lindsay et al. (2011)	CBA	New Zealand; age 18–64 years; stratification by ethnicity	Replace 5% (S1); 1% (S2); 10% (S3); 30% (S4) of car trips ≤7 km with bicycle	Physical activity; traffic incidents; air pollution GP	Health costs ($NZ; mortality, morbidity, activity-restriction); mortality; morbidity; adipose tissue; activity-restriction days
Rojas-Rueda et al. (2011)	CRA	Barcelona (Spain); 25,426 Bike-sharing users; age 16–64 years	Bike-sharing users replace all car trips with bicycle	Physical activity; traffic incidents; air pollution AcT	Mortality
Rabl and de Nazelle (2012)	CBA	Amsterdam (Netherlands); Paris (France)	Replace car trips 5 km with bicycle (S1); 2.5 km with walking (S2)	Physical activity; traffic incidents; air pollution AcT and GP; noise	Health costs (€; mortality)
Grabow et al. (2012)	BA	11 Metropolitan areas (USA); population of 31.1 million	Replace 50% of car round-trips ≤8 km with bicycle to improve air quality	Physical activity; air pollution GP	Health costs ($US; mortality, morbidity, activity-restriction, productivity-loss); mortality; morbidity; activity-restriction days
Olabarria et al. (2012)	BA	Catalonia (Spain); population of 80,552; age ≥17 years; stratification by sex	Replace car and motorcycle trips ≤5 min with walking	Physical activity	Health costs (€; mortality); mortality
Jarrett et al. (2012)	CBA	England and Wales (UK); urban areas with population of ≥200,000	Increase AT by walking 1.6 km, cycling 3.4 km and increase in PT (S1); short AT (S2)	Physical activity; traffic incidents	Health costs (£; health care, obesity costs)
Stipdonk and Reurings (2012)	RA	Netherlands; age ≥18 years; stratification by sex, age	Replace 10% of car trips ≤7.5 km with bicycle	Traffic incidents	Fatalities and injuries
Holm et al. (2012)	CRA	Copenhagen (Denmark); work/school commuters; age 15–69 years	Replace 50% of car trips 2–10 km and 33% of car trips 10–15 km with bicycle	Physical activity; traffic incidents; air pollution AcT	DALYs
Rojas-Rueda et al. (2012)	CRA	Barcelona (Spain); Metropolitan area (Spain); population of 3,231,458	Replace 20%; 40% of car trips 3.1 km 'inside Barcelona' (S1–S4); 6.4 km 'outside Barcelona' (S5–S8) with bicycle and PT	Physical activity; traffic incidents; air pollution AcT and GP	Mortality; life-expectancy
Creutzig et al. (2012)	CBA	Barcelona (Spain); Malmö (Sweden); Sofia (Bulgaria); Freiburg (Germany)	Transportation CO_2 reduction by business-as-usual 2040 (S1); AT 'pull' policies (S2); AT 'push' policies (S3); AT 'pull' and 'push' policies (S4)	Physical activity; traffic incidents; air pollution GP; noise	Health costs (€; mortality)
Dhondt et al. (2013)	CRA	Flanders and Brussels (Belgium); age ≥18 years; stratification by sex	20% fuel price increase	Physical activity; traffic incidents; air pollution GP	DALYs; life expectancy

Table 1 (*continued*)

Author (year)	Method	Study setting[a]	Active transportation mode shift scenarios[b]	Health pathways[c]	Health endpoints[d]
Woodcock et al. (2013)	CRA	England and Wales (UK); municipalities with population of >10,000 (excluding London)	Increase walking to 14.1 min and cycling to 6.4 min (S1); walking to 16.8 min and cycling to 9.5 min and increase PT (S2); walking to 21.6 min and cycling to 18.2 min and increase electric vehicle use (S3)	Physical activity; traffic incidents; air pollution GP	DALYs
Maizlish et al. (2013)	CRA	San Francisco Bay Area (USA), population of 9.1 million	Transportation CO_2 reduction by low-carbon driving (S1); walking 50% of distances ≤1.5 miles and cycling 50% of distances 1.5–5 miles (S2); optimization of physical activity and CO_2 reduction (S3)	Physical activity; traffic incidents; air pollution GP	DALYs
Rojas-Rueda et al. (2013)	CRA	Barcelona (Spain); Metropolitan area (Spain), population of 3,231,458	Replace 20%; 40% of car trips 3.1 km 'inside Barcelona' (S1–S4); 6.4 km 'outside Barcelona' (S5–S8) with bicycle and PT	Physical activity; traffic incidents; air pollution AcT and GP	DALYs; morbidity
Mulley et al. (2013)	CBA	Sydney (Australia)	Infrastructure projects stimulating a sufficiently active lifestyle	Physical activity	Health costs ($AUS; mortality, morbidity)
Schepers and Heinen (2013)	RA	Netherlands; municipalities with population of ≥10,000; stratification by age, population density	Replace 10% (S1); 30% (S2); 50% (S3) of car trips ≤7.5 km with bicycle	Traffic incidents	Fatalities and injuries
Woodcock et al. (2014)	CRA	London (UK); 578,607 bicycle-sharing users; age ≥14 years; stratification by age, sex	Bicycle-sharing system usage (2011–2012)	Physical activity; traffic incidents; air pollution AcT	DALYs
Deenihan and Caulfield (2014)	CBA[e]	Dublin area (Ireland); population of 141,777	Increase bicycle share from 1.7% to 2.5% (S1); 5% (S2); 10% (S3) by new cycling path	Physical activity	Health costs (€; mortality); mortality
Edwards and Mason (2014)	CRA	USA; age 20–65 years; stratification by age	Replace 6 mile car round-trips with bicycle	Physical activity; traffic incidents	Life expectancy
Macmillan et al. (2014)	CBA[e]	Auckland (New Zealand); population of 1.5 million	Infrastructure projects consisting of regional cycle network (S1); arterial segregated bicycle lanes (S2); self-explaining roads (S3); S2 combined with S3 (S4)	Physical activity; traffic incidents; air pollution GP	Health costs ($NZ; mortality, morbidity, activity-restriction days)
James et al. (2014)	CBA[e]	Boston area (USA); population of 4.8 million	Increase of PT fare price by 43% (S1); 35% (S2) and reduction of PT services	Physical activity; traffic incidents; air pollution GP; noise; health care access	Health savings ($US; mortality, morbidity); mortality; morbidity; obesity
Xia et al. (2015)	CRA	Adelaide (Australia); population of 1.1 million; stratification by age	Replace 5% (S1), 10% (S2) of car trips with bicycle; 20% (S3), 30% (S4) with PT; 40% (S5) with bicycle and PT	Physical activity; traffic incidents; air pollution GP	DALYs, mortality

AcT = active traveler; AT = active transportation; BA = benefit assessment; CBA = cost-benefit analysis; CRA = comparative risk assessment; DALYs = disability-adjusted life years; GP = general population; NOK = Norwegian Kroner; PT = public transportation; RA = risk assessment; and S = scenario.

[a] Study setting describes the geographic location and study population.

[b] Active transportation mode shift scenarios describe the scenarios of each study the health impact assessment was conducted for.

[c] Health pathways describe the health pathways that were considered by each study and that change their exposure distribution due to the mode shift to active transportation.

[d] Health endpoints describe the health endpoints the estimated health impact is expressed in. Mortality may include all-cause mortality, cardiovascular disease mortality, respiratory disease mortality, cancer mortality, falls, and traffic fatalities. Morbidities may include cardiovascular disease, respiratory disease, cerebrovascular disease, type 2 diabetes, cancer, dementia, depression, preterm birth, low birth weight, and traffic injuries.

[e] Cost–benefit analysis with comparison of estimated health benefits to AT intervention costs.

[f] [] Only partially considered or not quantified.

except Woodcock et al. (2009) only partially, used a linear DRF to describe the relationship between air pollution and health, with no modification of the DRF at higher exposure levels. All air pollution estimates for the general population obtained with a mode shift to AT resulted in reductions of all-cause mortality, respiratory disease, CVD, cancer, adverse birth outcomes, activity-restriction days, and productivity-loss. Air pollution estimates for the active traveler, however, resulted in increases of described health outcomes.

Noise

Three studies considered health impacts of noise exposure to the general population. Noise associations used came from technical reports. While James et al. (2014) assessed noise exposure by changes in traffic volume, Creutzig et al. (2012) and Rabl and de Nazelle (2012) used an indirect economic assessment of traffic-related noise exposure, including health costs; relying on a cost function dependent on vehicle-kilometers traveled, mode-type, time of day and urbanization. Noise costs were estimated to decline with a mode shift to AT, however, the noise health impact was not quantified independently (Appendix B.1).

Health endpoints

Health endpoints summarizing the overall estimated health impact of the studies were (1) all-cause or disease-specific mortality, including traffic fatalities; (2) morbidities, including CVD, respiratory disease, cerebrovascular disease, type 2 diabetes, cancer, dementia, depression, preterm birth, low birth weight, weight gain, overweight and obesity, adipose tissue, traffic injuries; (3) life-expectancy; (4) disability-adjusted life years (DALYs); (5) activity-restriction days and; (6) monetized health impacts, including health care costs, feeling-of-insecurity costs, activity-restriction costs, or productivity loss.

Table 2
Global health impact of a mode shift to active transportation.

Author (year)	Global health impact			
	Positive	Negative	Overall	Benefit–risk ratio or benefit–cost ratio
Mooy and Gunning-Schepers (2001)	Physical activity ↑[a]		Benefits only	NA
Sælensminde (2004)	Physical activity ↑ Insecurity (traffic safety) ↓		Benefits >[b] costs	Benefit–cost ratio: 2.9 (S3)–14.3 (S2)[c]
Boarnet et al. (2008)	Physical activity ↑		Benefits only	NA
Cobiac et al. (2009)	Physical activity ↑		Benefits < costs	Benefit–cost ratio: -1.86 (comparison of investment costs with cost offset)
Woodcock et al. (2009)	Physical activity ↑ Air pollution GP↓ Overweight and obesity ↓	Traffic incidents ↑	Benefits > risks	Benefit–risk ratio: 15.3 (S3)–15.5 (S4) (comparison of DALYs of physical activity, traffic incidents, air pollution for London)
Guo and Gandavarapu (2010)	Physical activity ↑ [Weight gain ↓][d]		Benefits > costs	Benefit–cost ratio: 1.87[c]
de Hartog et al. (2010)	Physical activity ↑ [Air pollution GP ↓]	Traffic incidents ↑ Air pollution AcT ↑	Benefits > risks	Benefit–risk ratio: 9[c]
Gotschi (2011)	Physical activity ↑ [Traffic incidents →]		Benefits > costs	Benefit–cost ratio: 1.3 (S3)–3.8 (S1)[c]
Lindsay et al. (2011)	Physical activity ↑ Air pollution GP↓ Adipose tissue ↓	Traffic incidents ↑	Benefits > costs	Benefit–cost ratio: 13.13 (S1)–43.8 (S4) (comparison of costs of physical activity, traffic incidents, air pollution)
Rojas-Rueda et al. (2011)	Physical activity ↑	Traffic incidents ↑ Air pollution AcT ↑	Benefits > risks	Benefit–risk ratio: 77[c]
Rabl and de Nazelle (2012)	Physical activity ↑ Air pollution GP↓ Noise ↓	Traffic incidents ↑ Air pollution AcT ↑	Benefits > costs	Benefit–cost ratio: 18.65 (comparison of costs of physical activity, traffic incidents, air pollution)
Grabow et al. (2012)	Physical activity ↑ Air pollution GP ↓		Benefits only	NA
Olabarria et al. (2012)	Physical activity ↑		Benefits only	NA
Jarrett et al. (2012)	Physical activity ↑ Obesity ↓	Traffic incidents ↑	Benefits > costs	Benefit–cost ratio: 23.61 (comparison of costs of physical activity, traffic incidents)
Stipdonk and Reurings (2012)		Traffic incidents ↑	Risks only	NA
Holm et al. (2012)	Physical activity ↑	Traffic incidents ↑ Air pollution AcT ↑	Benefits > risks	Benefit–risk ratio: 1.35 (comparison of DALYs of physical activity, traffic incidents, air pollution)
Rojas-Rueda et al. (2012)	Physical activity ↑ Traffic incidents (S3–S8) ↓ Air pollution GP↓	Traffic incidents (S1; S2) ↑Air pollution AcT ↑	Benefits > risks	Benefit–risk ratio: 58.70 (S2)–195.33 (S6) (comparison of mortality of physical activity, traffic incidents, air pollution)
Creutzig et al. (2012)	Physical activity ↑ Traffic incidents (S3; S4) ↓ Air pollution GP ↓ Noise (S3; S4) ↓	Traffic incidents (S1; S2) ↑Noise (S1; S2) ↑	Benefits > costs	NA
Dhondt et al. (2013)	Physical activity ↑ Traffic incidents ↓ Air pollution GP↓		Benefits only	NA
Woodcock et al. (2013)	Physical activity ↑ Traffic incidents ↓ Air pollution GP ↓		Benefits only	NA
Maizlish et al. (2013)	Physical activity ↑ Air pollution GP ↓	Traffic incidents ↑	Benefits > risks	Benefit–risk ratio: 7.59 (S2)–7.63 (S3) (comparison of DALYs of physical activity, traffic incidents, air pollution)
Rojas-Rueda et al. (2013)	Physical activity ↑ Traffic incidents (S3–S8) ↓ Air pollution GP ↓	Traffic incidents (S1; S2) ↑Air pollution AcT ↑	Benefits > risks	Benefit–risk ratio: 33.27 (S2)–362.25 (S5) (comparison of DALYs of physical activity, traffic incidents, air pollution)
Mulley et al. (2013)	Physical activity ↑		Benefits only	NA
Schepers and Heinen (2013)		Traffic incidents ↑	Risks only	NA
Woodcock et al. (2014)	Physical activity ↑	Traffic incidents ↑ Air pollution AcT ↑	Benefits > risks	Benefit–risk ratio: 6.18 (comparison of DALYs of physical activity, traffic incidents)
Deenihan and Caulfield (2014)	Physical activity ↑		Benefits > costs	Benefit–cost ratio: 2.22 (S1)–11.77 (S3)[c]
Edwards and Mason (2014)	Physical activity ↑	Traffic incidents ↑	Benefits > risks	Benefit–risk ratio: 6.18 (comparison of life years of physical activity, traffic incidents)
Macmillan et al. (2014)	Physical activity ↑ Air pollution GP ↓	Traffic incidents ↑	Benefits > costs	Benefit–cost ratio: 6 (S3)–24 (S4)[c]
James et al. (2014)[e]		Physical activity ↓ Traffic incidents ↑ Air pollution GP↑ Noise ↑	Risks only	NA
Xia et al. (2015)	Physical activity ↑ Air pollution GP↓ Traffic incidents ↓		Benefits only	NA

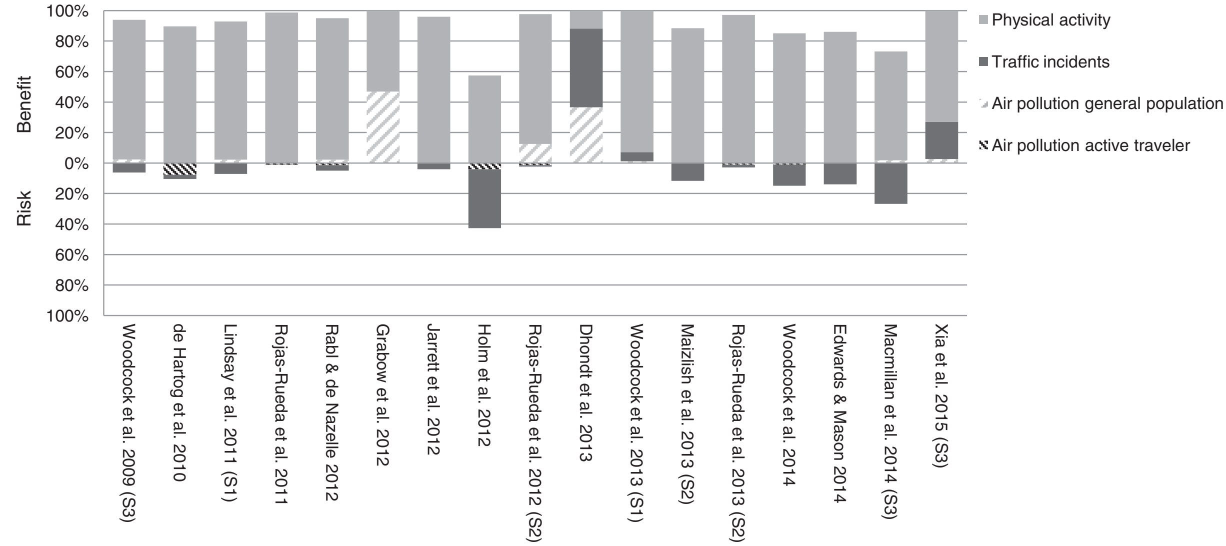

Fig. 2. Health pathway contribution to estimated health impact of a mode shift to active transportation[a,b]. (S) = scenario. [a] The health pathway contribution was calculated based on estimated change in health pathway exposure distribution and is comparing health benefits with health risks. Each health pathway contribution is expressed as a proportion of the overall estimated health impact of the scenario. If the study estimated multiple active transport scenarios, the health impact was calculated for the most conservative scenario (scenario with the smallest benefit–risk ratio or benefit–cost ratio). [b] The health pathway contribution could not be calculated for studies that assessed only one health pathway; for studies where the health impact could not be untangled from environmental and economic impacts; for studies where the individual health pathway contributions were expressed in different units. Therefore excluded: Mooy and Gunning-Schepers, 2001; Sælensminde, 2004; Boarnet et al., 2008; Cobiac et al., 2009; Guo and Gandavarapu, 2010;Gotschi, 2011; Olabarria et al., 2012; Stipdonk and Reurings, 2012; Creutzig et al., 2012;Mulley et al., 2013; Schepers and Heinen, 2013; Deenihan and Caulfield, 2014; James et al., 2014.

Health impacts

Estimated benefit–risk or benefit–cost ratios ranged from −2 to 360 (median = 9). Twenty-seven studies estimated health benefits of a mode shift to AT to outweigh associated risks or costs, irrespective of geographical context or baseline setting (Appendix B.2). The three studies that did not estimate an overall beneficial health impact were distinctive in their assessment approaches. Cobiac et al. (2009) calculated investment costs of their AT information and merchandise intervention to be excessive compared to the small change in AT behavior that the intervention produced. Stipdonk and Reurings (2012) and Schepers and Heinen (2013) assessed exclusively the risk of traffic incidents, to give a predicted overall increase in fatalities and injuries with a mode shift to AT.

Overall, however, net health benefits were estimated (Fig. 2). In all studies with multiple health pathways, except for Dhondt et al. (2013), health benefits of increased PA clearly outweighed estimated detrimental effects of traffic incidents and air pollution (Appendix B.3). These benefits contributed positively to at least 50% of all estimated health impact of AT. Dhondt et al. (2013) estimated the greatest benefits (52%) from reduced traffic incidents, but assumed a mode shift predominantly to safer transportation modes of public transportation and car-sharing (as passenger) and only a small proportion (2%) to walking and cycling (high risk modes).

Susceptible populations

Patterns of intra-population benefit differences were recognizable. The larger body of studies estimated older people (typically >45 years) to benefit more overall from a mode shift to AT than younger people (de Hartog et al., 2010; Rojas-Rueda et al., 2011, 2012, 2013; Dhondt et al., 2013; Woodcock et al., 2014; Edwards and Mason, 2014; Xia et al., 2015). Albeit, when assessing only traffic safety, younger people (typically <30 years) were estimated to experience a road safety gain with a mode shift to AT (de Hartog et al., 2010; Stipdonk and Reurings, 2012; Dhondt et al., 2013; Schepers and Heinen, 2013). Nevertheless, in settings where AT increases the incident risk, AT appears especially hazardous for younger people, relative to the proportional change in baseline mortality (Edwards and Mason, 2014; Woodcock et al., 2014).

In spite of Edwards and Mason (2014) finding no sex differences, overall males were estimated to benefit more from AT than females (Olabarria et al., 2012; Dhondt et al., 2013; Woodcock et al., 2014). Assessing only traffic safety, Stipdonk and Reurings (2012) found male cyclists to be at increased injury risk, while contradictorily Woodcock et al. (2014) found female cyclists to be at increased injury risk. Finally, disadvantaged ethnic sub-populations were estimated to benefit more from AT than the general population (Lindsay et al., 2011).

Notes to table 2:
AcT = active traveler; AT = active transportation; DALYs = disability-adjusted life years; GP = general population; NA = not available/only health benefits found/risks not considered/incomparable units; and S = scenario.

[a] (↑) Increase in exposure level. (↓) Decrease in exposure level. (→) No change in exposure level.

[b] >/< Relational operators indicating direction of health association.

[c] Benefit–cost ratio or benefit–risk ratio was taken as reported directly from the study. Reported cost–benefit ratios may include environmental and economic impacts and may compare to investment costs. If the study did not report a ratio and if possible, a benefit–risk or benefit–cost ratio was calculated based on change in health pathway exposure distribution, except for Cobiac et al. (2009) where only a comparison between investment costs and cost offset was possible.

[d] [] Only partially considered or not quantified.

[e] James et al. (2014) estimated health impacts of a modal shift from (walking to) public transportation to private vehicle use. The estimated health impact is exclusively negative, i.e. no health benefits from such a shift, which is interpreted by us as a theoretical health gain through active transportation.

Discussion

Consistently, the vast majority of the reviewed HIAs estimated substantial net health benefits with a mode shift to active transportation (AT). Estimated benefits were largely due to increases in PA levels, which greatly outweighed associated detrimental effects of traffic incidents and air pollution exposure. Noise impacts were only considered secondary. The large range of benefit–risk and benefit–cost ratios observed may be attributable to distinctive HIA approaches, different assumptions on health pathways, scenario design and baseline population parameters.

Physical activity

Estimated gains in PA from AT constituted at least half of the total health impact, except in Dhondt et al. (2013). Uncertainties remain, however, regarding assumptions on possible PA substitution (from another domain, with AT). There remains limited understanding on the relationship between transportation PA and total PA (Cavill et al., 2008). On the one hand, studies show independent health benefits from PA gained by AT, even after adjusting for other domains of PA (Andersen et al., 2000; Matthews et al., 2007; Hamer and Chida, 2008; Kelly et al., 2014). On the other hand, studies have shown uncertainty as to how much AT adds to total PA (Forsyth et al., 2008; Thomson et al., 2008; Wanner et al., 2012). This uncertainty is attributed to two things: (1) the failure of detecting significant associations; and (2) the argument that total PA is predetermined by the social environment as people who do more leisure time PA do less for other purposes and vice versa. Nonetheless, recent longitudinal studies estimated significant contributions of PA from AT to overall PA, without reducing participation in other PA domains (Sahlqvist et al., 2013; Goodman et al., 2014). Thus, the assumption of a 1:1 gain in overall PA (i.e. no substitution) by all reviewed HIA studies appears plausible.

The shape of the applied DRF significantly impacts the PA benefit magnitude. As done by a few studies, a more biologically plausible approach is the application of a non-linear DRF which implies that health benefits vary in magnitude for different PA levels. Non-linearity coheres with results of a meta-analysis showing a strongly curvilinear relationship between PA and all-cause mortality, with the greatest benefits occurring for inactive people becoming moderately active (Woodcock et al., 2011). However, to apply a non-linear DRF, knowledge on baseline PA is essential. Given that in most cases data on baseline PA was not available, a linear DRF was used in which case no assumptions about baseline PA are required. Nevertheless, a linear DRF assumes equal changes in health benefits for active and non-active people; this assumption can lead to under-estimations of health benefits of PA for non-active people and to over-estimations for active people (Appendix C.1) (Woodcock et al., 2011; Rojas-Rueda et al., 2013).

Traffic incidents

Estimated health risks by traffic incidents are minor compared with health benefits gained by PA. Generally, an increase in traffic incidents resulting in fatalities or injuries was estimated with increases in walking and cycling. Shifting to active modes may increase incident risk as these are considered high-risk modes (Teschke et al., 2012; Wegman et al., 2012; Zegeer and Bushell, 2012). Moreover, an increase in single-mode incidents ('slipping') is projected (Schepers and Heinen, 2013).

Several studies, nevertheless, estimated their AT mode shift scenarios to lead to reduced incidents. These findings are due to three assumptions: (1) overall reduced motorized traffic volume; (2) a mode shift to safer transportation modes such as public transportation and car-sharing (as passengers) may reduce incidents (Dhondt et al., 2013); and (3) the concept of 'safety in numbers' assumes a less than proportional increase in incidents, with increased walking and cycling share and acquired modal co-existence (Jacobsen, 2003; Elvik, 2009). In this context, one study found that the risk for cycling casualties decreased in communities with a higher cycling proportion (Vandenbulcke et al., 2009). However, uncertainties remain regarding the location-specific threshold level until a 'safety in numbers' effect may occur (Macmillan et al., 2014). Thus, there are suggestions that secure infrastructure measures must precede traffic safety and increases in AT ('numbers in safety') (Bhatia and Wier, 2011).

Generally, the injury burden of AT might be underestimated due to potential under-reporting of minor injuries. Two studies found that only 7% of all cycling incidents were reported in police statistics and chances for reporting increased with injury severity (Aertsens et al., 2010; de Geus et al., 2012). Another study found that single-mode incidents accounted for 40% of all bicycle incidents with 70% resulting in minor injuries (Tin Tin et al., 2010). Moreover, the incident risk is dependent on many setting-specific variables not currently comprehensively considered (Mindell et al., 2012; Wegman et al., 2012). Distance or time traveled, infrastructure provisions, traffic volume, modal split, conflict types, speed and road type traveled, kinetic energies as well as age and sex effects all affect incident risk.

Air pollution

Air pollution exposure was estimated to have small health impacts, with small benefits to the general population and small risks to the active traveler. Only two studies estimated larger air pollution improvements, but their studies assumed substantial reductions in motorized traffic volume (Grabow et al., 2012; Dhondt et al., 2013). While population health benefits emerge from reductions in motorized traffic volume and associated emission reductions, the risk to the active traveler is more complex to assess. On the one hand, walkers and cyclists may experience lower direct TRAP exposure than vehicle occupants, especially while traveling on segregated sidewalks or bike lanes (Boogaard et al., 2009; MacNaughton et al., 2014). On the other hand, increased ventilation rate resulting from physical strain increments the uptake of pollutants at least twofold (Zuurbier et al., 2010; de Nazelle et al., 2012). Taking into account ventilation rate, lung deposition and potential increases in travel time while substituting motorized transportation, estimations need to be revised upwards (Briggs et al., 2008; Int Panis et al., 2010).

Using air pollution risk estimates from elsewhere involves uncertainty because air pollution components are location and source specific (Stevens et al., 2014). $PM_{2.5}$ is a commonly-used proxy for exposure to all fossil fuel combustion sources. It has been suggested to be the most health relevant pollutant and is used in the Global Burden of Disease Study (Lim et al., 2012). Nevertheless, $PM_{2.5}$ cannot be differentiated by components, source or toxicity (Burnett et al., 2014). Thus, there is concern that $PM_{2.5}$ underestimates the health effects of incomplete fuel combustion (Janssen et al., 2011). All studies applied linear associations for air pollution, except Woodcock et al. (2009) for Delhi. Instead, a log-linear DRF for $PM_{2.5}$ was used as yearly average concentrations in Delhi exceeded 40 μg/m^3 and a linear DRF would predict implausible risks. Recent new evidence suggests that the relationship between $PM_{2.5}$ and excess mortality does not necessarily follow a linear function for the entire exposure range (Burnett et al., 2014).

Noise

So far, health impacts of traffic noise have mostly been neglected in HIA, despite assumptions of reductions in motorized traffic volume decreasing noise exposure to the general population. However, there remains inconclusive evidence to what extent traffic noise and TRAP are correlated (Foraster, 2013), given that both exposures are associated with CVD and diabetes (Babisch, 2014; Dzhambov, 2015). As the majority of risk estimates used for air pollution has not been adjusted for noise, attempting to include noise as an independent health pathway may confound health impact estimations.

Susceptible populations

Uncertainties persist in intra-population benefit differences. Overall, older people are estimated to benefit more from a mode shift to AT than younger people (Appendix C.2). Increased benefits from PA for older people are seen mainly because older people are at increased risk for chronic degenerative disease and PA can substantially reduce the absolute risk for disease development (Chodzko-Zajko et al., 2009; Vogel et al., 2009). Therefore, in older people the benefits of PA are estimated to greater outweigh the detriments of traffic incidents and air pollution exposure (de Hartog et al., 2010; Dhondt et al., 2013; Edwards and Mason, 2014; Woodcock et al., 2014; Xia et al., 2015). However, it remains inconclusive whether older people benefit differently from the same PA exposure than younger people, despite recent research findings indicating the latter. A systematic review found a larger mortality risk reduction for older people compared to younger people (RR = 0.78 vs RR = 0.81; 11 MET-hrs/week) (Woodcock et al., 2011). Assumptions that health benefits of PA are in fact long-term benefits support the argument that older people benefit more overall from AT (Edwards and Mason, 2014).

When assessing exclusively traffic safety of a mode shift to AT, in settings with low injury rates, younger people are estimated to experience a traffic safety gain, while older people are more vulnerable (de Hartog et al., 2010; Stipdonk and Reurings, 2012; Dhondt et al., 2013; Schepers and Heinen, 2013). Nevertheless, in settings where substituting AT for driving substantially increases the risk for incidents, there might be more relative harm for younger people, as injury and death at younger ages translate into a larger burden of disease due to lower baseline mortality and higher statistical life-expectancy (Edwards and Mason, 2014; Woodcock et al., 2014).

While one US study did not find sex differences in benefits (Edwards and Mason, 2014), three European studies estimated males to benefit more overall than females from a mode shift to AT: (1) males are less likely achieve PA recommendations (Olabarria et al., 2012); (2) the two different sexes are predicted to have distinctive disease risks (Woodcock et al., 2014); and (3) males benefit more from reduced motorized traffic incident risk (especially while switching to low risk modes of public transportation and car-passenger) (Dhondt et al., 2013). Despite cycling being a high risk mode for both sexes, males are said to have a higher injury risk as drivers, cyclists and pedestrians compared to females (Mindell et al., 2012). Nonetheless, one study estimated female cyclists to be at increased fatality risk in London, but also expressed local-specificity of their results given the typically lower risk faced by females (Woodcock et al., 2014).

As for older people, pronounced benefits for socially disadvantaged or ethnic sub-populations can be related to increased chronic disease incidence (Lindsay et al., 2011; Fang et al., 2012). However, differences in intrinsic motivations for AT engagement and intention–behavior relationships among different social classes need to be considered (Conner et al., 2013).

Uncertainties in health impact estimations

The reviewed HIA studies carry uncertainties in the estimations of quantitative health impacts, which emphasizes that HIA remains an indicative rather than an empirical research tool (Parry and Stevens, 2001). Benefit–risk and benefit–cost ratios can only be interpreted as an indication of the magnitude of expected health impacts, as underlying HIA modeling assumptions vary largely across studies. As typically local risk estimates for PA, air pollution and noise were not available, a multitude of risk estimates taken from elsewhere were applied. This limits comparability across studies. Likewise, uncertainties about strengths of associations and shapes of DRFs limit comparability of studies, despite the significant influences on the benefit magnitude.

Benefit estimations are sensitive to the contextual setting and population parameters. Health impact estimations depend on baseline prevalence of AT, baseline exposure to health pathways and the general health status of the population. Assumptions of a 'healthy-walker/cyclist effect' minimize benefit estimations by assuming that only healthy people with a low baseline disease risk choose AT (Macmillan et al., 2014). Moreover, it is uncertain to what extent the mode shift scenarios reflect reality as individuals' intrinsic motivations for AT engagement have not been considered yet (Kroesen and Handy, 2013). Despite a recent meta-analysis finding no significant effect for efficacy of behavioral interventions for transportation behavior change (Arnott et al., 2014), another recent systematic review suggests that a combination of behavioral and structural (workplace, built-environment, AT facilities) interventions may best increase AT engagement (Scheepers et al., 2014). In this regard, culture can reinforce AT behavior where it is common, but has opposing effects where it is uncommon (Pucher et al., 2010). There is also concern for decay of behavioral effects over time (Cobiac et al., 2009; Hoffman et al., 2012).

To estimate longevity of AT health effects one needs to consider time-lags in health benefits and risks. PA benefits are predominantly long-term in nature (Reiner et al., 2013; Chevan and Roberts, 2014), whereas injuries from traffic are immediate detriments. Taking time-lags into consideration can substantially alter benefit estimations. Delayed receipt of health benefits from PA makes AT less appealing for younger people, but reinforces the importance for older people (Edwards and Mason, 2014). AT, however, might not be the most convenient choice of transportation for older people. Making AT safe and convenient (and normal) may be the key to reaching this population.

The effects of AT on health equity remain uncertain. On the one hand, a study found higher uptake of walking and cycling infrastructure by socio-economically advantaged individuals (Goodman et al., 2013). On the other hand, two studies found that children from lower income households were more likely to use AT, suggesting that AT may be able to narrow health inequity (D'Haese et al., 2014; Gray et al., 2014). Supporting the latter, two studies in adults found greatest AT health benefits for disadvantaged ethnic sub-populations (Aytur et al., 2008; Lindsay et al., 2011). Yet, AT land-use improvements and facilities are mostly implemented in high income areas which also report more traffic safety and less crime (Aytur et al., 2008; Sallis et al., 2011).

Future research on the health impacts of AT should aim to better consider acute impacts on quality of life, including physiological and mental indicators (e.g. less back pain, increased mobility, mental well-being and happiness) and integrate impacts outside of the health domain, such as the effects on social capital, crime, or productivity. Future studies should also look more in-depth into effects of age, sex and social class, in times of global shifting in population age, gender equality and social equity. All studies, except Woodcock et al. (2009), were exclusively conducted in high income settings, leaving uncertainty about how results can be transferred to low and medium income settings. Moreover, children have been underrepresented, even though AT is accessible for children and estimated health impacts presumably affect them as well. Currently, no studies exist that estimate health impacts of other modes of transportation that involve PA, such as skates or e-bikes. However, studies may soon be appropriate for e-bikes, given their rapid market growth and importance for AT.

While care is needed when interpreting the results of HIA, the reviewed studies show net health benefits of a mode shift to AT, irrespective of geographical context and varying HIA modeling assumptions. HIA is valuable to improve the understanding of the interrelationship between transportation and health and can assist in optimizing health gains of non-healthcare interventions (Thomson et al., 2008).

Limitations and strengths

For the first time, studies conducting quantitative HIA of a mode shift to AT were systematically reviewed. We provide evidence of net health benefits of AT. However, publication bias is plausible as HIA in transportation is frequently conducted for intervention planning outside the peer review framework, such as the gray literature (Appendix D.1). Studies with negative findings may also less likely be published. Despite such limitations, the systematic search strategy and comprehensive inclusion criteria limit selection bias. The review of both public health and transportation databases, the absence of a time restriction and limited language constraints ensure that the existing body of evidence was captured.

Conclusions

We conclude that net health benefits of AT are substantial, irrespective of geographical context. Projected health gains by increases in PA levels exceed detrimental effects of traffic incidents and air pollution exposure. Thus, we encourage the promotion of AT, as associated health risks are minor.

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Conflict of interest statement

All authors have completed the Preventive Medicine conflict of interest policy form and declare that there are no conflicts of interest.

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Supplementary Data

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