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Travel behaviour and health: a conceptual model and research agenda

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Abstract

Objectives. This paper proposes a conceptual model of the complex relationships between travel behaviour and health. In addition it gives a research agenda providing an overview of challenges for future research.

Methods. We review the relevant literature in the areas of public health, land use and transportation that address issues related to health and travel and their underlying mechanisms. We do not aim to give a full review of the literature but to underpin the conceptual model.

Results and conclusions. We conclude that research can easily come to the 'wrong' conclusions if the complex causal relationships that exist between relevant factors are overlooked. In particular, ignoring contradictory effects for specific socio-demographic groups, (residential) self-selection effects, substitutions of different forms of activity, and reverse causalities may lead to overestimation of the effect of policies. For example, travel-related physical activity might interact with other physical activity, self-selection effects may influence the complex relationships between travel behaviour and health, and people's health may influence their walking or cycling behaviour.

Based on the conceptual model we present a research agenda. A first research challenge is to explore the combined effect of travel behaviour related determinants for health effects (physical activity, air pollution intake, injuries, and subjective well-being) on health. A second challenge is exploring the interactions between travel-related physical activity and other physical activity. Thirdly, the importance of attitudes and attitude formation, specifically health-related attitudes and self-selection processes related to travel behaviour, is an important research topic. Fourthly, it is important to explore the relationship between cycling levels and injury risks, because risks seem to be correlated with cycling levels: the more people cycle, the lower the injury risks. Fifthly, we think it is important to study the relevance of walking and cycling related self-selection effects. A sixth challenge relates to transport innovations.

Highlights

A conceptual model of the complex relationships between travel behaviour and health

Research can easily come to the 'wrong' conclusions

An overview of the challenges for research

Keywords

Conceptual model, research agenda, literature review, health, travel, physical activity, exposure, injury risks

1. Introduction

Over the last decade there has been increased research interest in the relationships between travel behaviour and health, partly fuelled by the recognition that an increase in the use of active modes may decrease obesity (e.g. Bassett et al., 2008), and by the wider health benefits of these modes (e.g. De Hartog et al., 2010). Indeed, the health benefits of these modes may be substantial. For example, Saelensminde (2004) concludes that of all the benefits of cycle infrastructure measures in Norwegian cities over half are health related. Other studies, especially in the domain of epidemiology and public health, have addressed the travel-related health effects caused by exposure to pollutants during travel (e.g. Handy, 2014; Schepers et al., 2015), and traffic safety studies (e.g. Wegman, 2014) have investigated the health hazards stemming from involvement in traffic collisions and/or falls during travel. The effects of travel behaviour on health can therefore be different, both positive and negative, and vary depending on the travel mode and circumstances.

To the best of our knowledge there is as yet no comprehensive overview of the relationships and contributing factors to travel behaviour and health, despite the increasing body of knowledge about the relationships between the two. In our view, a comprehensive overview should not only describe the associations between travel behaviours and health outcomes, but also touch upon causalities, spurious effects, interaction effects and group specific effects. This paper aims to present such an overview, and shows that if important factors are not included in research, one can easily come to the 'wrong' conclusions. We do not aim to give a fully-fledged review of the literature – there is abundant literature in some of the areas we cover (see, for example, Handy (undated) for an overview of the literature in the area of built environment impacts on physical activity, or Handy (2014) or Cohen et al. (2014) for an overview of the connections between travel and health). A full review of all the relationships covered by the model would be way too much for one journal paper. We rather confine this paper to examples which underpin the conceptual model. In addition, we aim to demonstrate how the health effects of policies and behaviours in different domains (such as exposure, physical activity or safety) are related and may reinforce or counteract each other. A second aim of this paper is to provide a research agenda for research in the area of health and travel. Our paper is limited to land transportation and excludes air travel (and the related health effects due to radiation levels and lack of movement).

This paper is structured as follows. Section 2 presents and discusses the conceptual model. Section 3 presents a research agenda. Section 4 provides a summary of the main conclusions.

2. The conceptual modal

The WHO defines health as 'a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity' (http://www.who.int/about/definition/en/print.html). We also consider health to be broader than the absence of disease or infirmity, but adopt a less broad approach than the WHO, by excluding the social dimension because it is only indirectly related to the links between travel behaviour and health. We consider mental and physical wellbeing as separate factors, which are however interrelated. The reason is that this approach allows us to better conceptualize the links between travel behaviour and mental well-being, and subsequently physical well-being. To be consistent with generally used terminology, we will in the remainder of the paper use the term 'health' to denote physical health, and 'subjective well-being' to denote mental well-being. There is an obvious relationship between subjective well-being and mental health. However, whereas mental health studies focus on symptoms of mental illness, such as depression or anxiety, well-being studies focus on a wider spectrum of mental states, which also differentiate between people without symptoms of mental illness. In this study we refer to the broader meaning of subjective well-being. To make the model operational we therefore conceptualize health as determined by the following components:

- Level of physical activity
- Air pollution intake
- Casualties
- Subjective well-being

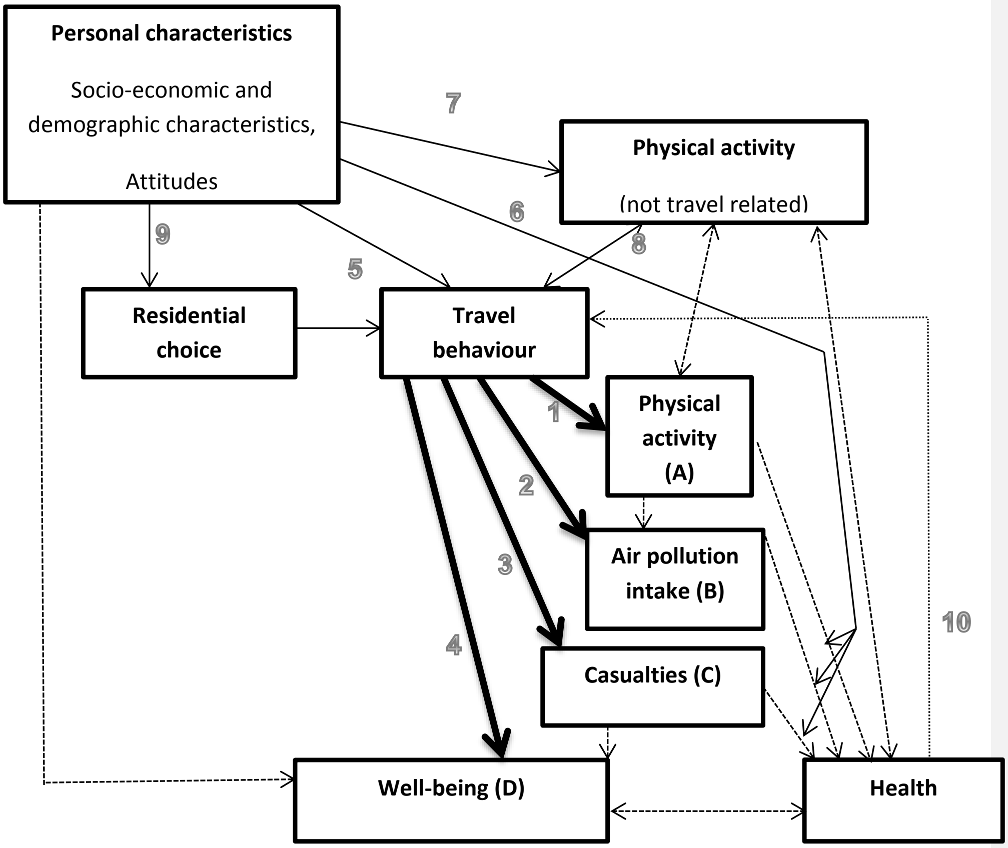
These factors are interrelated: for instance, using active modes may result in increased subjective well-being (Olsson et al., 2013), but may also lead to crashes/falls which would decrease the use of these modes, for example because people become disabled or scared to use these modes (see Lee et al., 2015). As another example, high concentrations of pollutants are not only unhealthy in themselves, but may also deter people from cycling or walking, with negative health effects.

Figure 1 presents the conceptual model. We depart from the notion that the health effects of travel arise via various paths, including physical activity (component A in Figure 1), exposure to and intake of air pollutants (B), and involvement in collisions/falls (C). These effects on health are well documented (see, for example, Handy (2014) or Cohen et al. (2014) for an overview; we do not discuss this literature in detail in this paper). In addition, we assume that subjective well-being (D) is related to health, albeit a less straightforward relationship and the causality is debatable. Subjective well-being is commonly defined as a combination of a person's assessment of his/her quality of life and satisfaction with life, and his/her affective state, as the net effect of positive and negative emotions. Studies of subjective wellbeing consistently show health to be the most important determinant of life satisfaction (e.g. Van Praag et al., 2001). On the other hand, it can be argued that a sufficient level of satisfaction with life and good mood are beneficial to one's physical health. Diener and Chan (2011) extensively review empirical longitudinal studies in this area. They report evidence that an individual's current affective state (induced by experimental manipulations) influences physiological health indicators measured afterwards such as blood pressure, inflammatory activity or immune functioning. In addition, they report many longer term longitudinal studies showing evidence for the impact of subjective well-being on longevity and developing diseases various years to decades later.

The conceptual model includes the dominant relationships important for the relationships between travel behaviour and health, but not all the relationships that exist between the categories of variables. For example, residential choice may have an impact on subjective well-being, experiences with specific transport modes may influence the attitudes towards these modes, and residential choice may influence the air pollution intake because the concentrations of pollutants vary spatially. In addition we realize that health also depends on other behaviours, like smoking and drinking, and on genetics, and these factors may relate to Figure 1 in complex ways. However, for reasons of demarcation and to reduce complexity these factors are not discussed in this paper. It is also important to realize that the main aim of the transport system is to provide access to destinations, both for passenger and goods transport. Limiting ourselves to passenger transport, the transport system allows people to participate in activities like working, shopping, visiting family and friends, cultural and health care facilities. It applies to all people, including vulnerable groups of people such as those who cannot drive or easily travel using active modes and public transport, such as people with disabilities, the elderly and children. High levels of access can improve subjective well-being. For a discussion of social exclusion we refer to Lucas (2012), for a broader conceptualisation of the transport system and societal relevant effects we refer to Van Wee (2013), and for the links between transport, social exclusion and health we refer to Mackett and Thoreau (2015).

The model includes relationships relevant for the understanding of causalities (dashed lines, not numbered), but not directly for the relationships between travel behaviour and health – these are not discussed in our paper.

Figure 1: conceptual model for the relationship between travel behaviour and health.



2.1 Dominant first order relationships

We first discuss the dominant direct relationships between travel behaviour and health (bold lines in Figure 1), in other words:

- Travel behaviour and physical activity (arrow 1)
- Travel behaviour and pollution intake intake (arrow 2)
- Travel behaviour and casualties (arrow 3)
- Travel behaviour and subjective well-being (arrow 4)

We label these relationships as 'first order' relationships because travel behaviour directly affects these factors, and these factors directly affect health. We call all other factors as conceptualized in Figure 1 'second order' relationships. There is much more research on these first order effects than on the second order effects.

Travel and physical activity (arrow 1)

It has been established that to promote and maintain health, adults should engage in 150 minutes of moderate physical activity (MPA) or 75 minutes of vigorous physical activity (VPA) per week, or a pro rato combination of the two (US Department of Health and Human Services, 2008; UK Department of Health, 2011). Walking and cycling, as part of the daily activity and travel patterns of many, can contribute to meeting these requirements. (Handy, 2014).

It is beyond the aim of this paper to discuss the health effects of travel. Examples of papers on this topic include Morris and Hardman (1997), Hu et al. (2000) and Manson et al., 2005) who discuss the health effects of walking, , and

Wagner et al. (2001) and (Oja et al., 1998) discussing the health effects of walking and cycling.

What is important from this literature is that the positive health effects seem to increase with the intensity of the activity, and a minimum weekly duration is required to achieve these effects. In terms of travel behaviour, this implies that travel mode choice influences the amount of physical activity, with walking and cycling leading to more physical activity, and cycling to a greater extent than walking. Since the time spent in walking and cycling obviously influences the amount of physical activity, it matters for what destinations walking or cycling is used, and route choice may also have an impact, as it influences distance and trip duration. Finally, the choice of travel speed will influence the amount of physical activity at specific levels, with different health effects.

Travel behaviour and air pollution intake (arrow 2)

Air pollution intake relates to the intake by drivers and passengers, among people cycling and walking, and people travelling by underground. Pollutant concentrations are highest on the roads, and decrease as distance from the road increases (Janssen et al., 2002), so drivers are exposed to relatively high concentrations. Based on an overview of the literature, Van Wee (2007) concluded that in vehicles, the concentrations are between 1.5 and over 10 times higher than in the ambient air, and that the difference between concentrations is greater for CO, benzene and NO_2 compared with PM2.5 and PM10. So drivers, passengers, and people walking or cycling on or very close to roads are exposed to high concentrations of pollutants. Emissions include emissions from road vehicles driving on the same road (or adjacent road if they cycle on cycle tracks) as well as emissions from vehicles driving on roads further away from where they cycle or walk. For literature we refer to Van Wee (2007). In general the concentration depends on the density and composition (in terms of age and engine/fuel type) of the motorised traffic and the distance to these sources. For a recent paper on the importance of distance for exposure to vehicle pollutants for cyclists: see Schepers et al. (2015). In addition, ambient factors such as temperature, wind speed and the morphology of the built environment and trees play a role in the dispersion of pollutants and consequently concentrations and exposure. Although cyclists are exposed to lower concentrations than drivers, cyclists inhale more air than car drivers, due to their physical activity – in Figure 1 this effect is conceptualized via the arrow from 'physical activity' to 'air pollution intake'. Consequently they 'inhale a little more benzene and CO, and significantly more NO_2 than car drivers' (Van Wee, 2007, based on several references). In addition, the exposure of cyclists and pedestrians depends on travel speed. With higher walking and cycling speeds, breath rates will increase, and more pollution is inhaled per unit of time (Nyhan et al., 2014). However, higher speeds also imply a shorter duration of exposure. Laboratory experiments (McNabola et al., 2007) as well as field tests (Nyhan et al., 2014) suggest that the latter effect prevails, leading to less exposure when cycling or walking faster.

People travelling by underground may be exposed to high concentrations of PM originating from mechanical friction processes. Literature in this area is scarce. Sahin et al. (2012) found concentrations of particles containing Fe and Cu in six subway stations in Istanbul to be significantly higher than the levels they found in urban air quality stations. Chen and Yan (2011) found PM concentrations to be higher in Taipei underground environments than in ground level indoor environments, and CO concentrations to be lower. Cohen et al. (2013) discuss regulations for pollutants in metros.

The health effects of exposure are diverse and obviously depend on the substance to which one is exposed. For a detailed overview we refer to Handy (2014). Negative health effects include cardiovascular diseases, respiratory health problems (asthma, lung damage), eye and throat irritation, high blood pressure, brain and kidney damage, neurological disorders and cancer, amongst others. The extent to which these effects occur depends on the duration and accumulation of exposure, but also to personal characteristics. For instance the elderly, infants or pregnant women are more sensitive to certain pollutants. In addition, one's health status, resulting from certain behaviors (such as smoking) has an impact on the health effects resulting from exposure.

In addition to exposure to pollutants resulting from participating in travel, people are exposed to concentrations of pollutants resulting from living or staying near roads, but because this paper is limited to travel behaviour related effects this effect is not further discussed.

Travel behaviour and casualties (arrow 3)

Travel includes a certain risk. No mode is risk free (though in the Japanese High Speed Rail system no fatalities have occurred since its introduction in 1964 – see http://en.wikipedia.org/wiki/Shinkansen). Risks are mode-specific (Wegman, 2014), and within road-related modes they vary between road types (Amoros et al., 2003). In the Netherlands fatalities per million traveller kilometres for car are 2.4, cycling 11, walking 21, and motorized two-wheelers 64/65 (depending on the two-wheeler category) (Wegman, 2014; data apply to the period 2004-2007). Note that risk factors are highly context specific, and even more so for cycling than for, for example, driving, due to the huge differences between countries where cycling is common (such as Denmark and the Netherlands) or not (such as in the USA). However, it is not at all straightforward to estimate the risks of additional cycling (and probably also walking), for several reasons. First, an increase in cycling levels is associated with a decrease in risks of fatal and non-fatal casualties (Jacobsen, 2003; Elvik, 2009). However, the exact context dependent relationships between risks and cycling level are still unclear. Elvik (2009) concludes that the decrease in risks per kilometre far outweigh the increase in cycling levels, resulting in a decrease in the total number of fatalities, but it is important to realize that this can only apply after a certain threshold value: if no one cycled, there would be zero fatalities. So for very low levels of cycling this decrease cannot apply. Van Wee and Börjesson (2015:120) add to this debate that 'when cycling levels increase there may still be an increase in the number of accidents involving no motor vehicle, especially accidents such as cyclists falling or hitting an object, so specific accident categories need to be distinguished'. Secondly, competing trips should be compared, comparisons should not be based on aggregate average risks. People do not substitute long interurban car trips of, for example, 80 kilometres, for cycling, but might be inclined to substitute 4 kilometre urban trips. In that case a comparison of risk factors for urban roads only would be more suitable to estimate safety impacts. A third reason is that in many countries there is a lack of data on cycling behaviour (Handy et al., 2014), Denmark and the Netherlands being the exceptions, and a lack in the quality of the way cycling is included in mainstream transport models, even in countries with a cycling tradition. Finally, the complex relationships between modes and risk are impacted by different risk-taking behaviours dependent on age and gender, and the different age and gender characteristics of users of different travel modes (Mindell et al., 2012).

For an elaborate discussion on the complex relationships between cycling and risks see Van Wee and Börjesson (2015).

Travel behaviour and subjective well-being (arrow 4)

Travel may influence subjective well-being in both direct and indirect ways. The direct influence of travel emerges via exposure to the physical and social environment when travelling. The indirect influence is related to the instrumental role of travel for participating in out-of-home activities that satisfy needs such as social interaction, achievement of self-realisation. We discuss both effects in this section.

Travellers are exposed to their travel environment, which may trigger emotional responses, resulting in a certain mood. If aggregated, and especially in the context of recurrent trips, such responses have an impact on an individual's subjective well-being. Most studies focus on the direct effect of travelling by different modes on affect or mood (e.g. Olsson et al., 2013). Since different travel modes offer different travel environments, levels of interaction with the outside world, and levels of physical activity, their impact on mood is likely to differ. Studies carried out in different geographical contexts (Olsson et al., 2013; Mao et al., 2015; St-Louis et al., 2014; Martin et al., 2014) consistently indicate that travel by active modes (walking and cycling) results in higher levels of momentary well-being as compared with the car, and public transport results in lower levels of subjective well-being.

The positive effect of using active modes may be because walking and cycling offer better opportunities to enjoy the scenery and bring more enjoyment (Gatersleben and Uzzel, 2007). The physical activity involved in walking and cycling may also contribute to the subjective well-being benefits (Ekkekakis, 2008; Holloway, 2010). For specific groups (e.g. elderly, children) walking may contribute to a sense of autonomy and mastery, and hence have a positive impact on mood and subjective well-being (Ettema and Smajic, 2015; Ziegler and Schwanen, 2011). The social aspect of walking, through interactions with the neighbourhood, may also add to the positive effects (Ziegler and Schwanen (2011).

Car driving has been found to be experienced as pleasant in itself (Gatersleben, 2007). Driving may also affect mood via driving circumstances. Congestion and long commutes have been found to be associated with stress and lower levels of subjective well-being (Novaco et al., 1990). However, also the layout and appearance of the road may have an impact on the experience of driving (Ettema et al., 2013).

Using public transport consistently leads to lower levels of experienced subjective well-being (Olsson et al., 2013; Mao et al., 2015; St-Louis et al., 2014; Martin et al., 2014). Friman and Gärling (2001) found that the occurrence of critical incidents while using public transport, such as rude personnel or undesired interactions with fellow travelers, may evoke negative emotions and influence subjective well-being. Across travel modes, the literature suggests that factors such as a longer trip duration, crowding level and congestion lead to lower levels of affect. The literature further suggests that structural travel circumstances that are experienced on a daily basis may influence an individual's life satisfaction. For instance, Frey and Stutzer (2008) found that a longer commute time leads to lower life satisfaction.

A second way in which travel influences subjective well-being is by allowing access to meaningful activities (De Vos et al., 2013; Ettema et al., 2010). Pychyl and Little (1998) and Oishi et al. (1999) suggest that subjective wellbeing significantly depends on progress towards one's life goals, and that activities, organized in projects, are important tools to make such progress. However, opportunities to engage in such activities depend on both the availability of travel options and the distance to relevant activity locations. Studies on travel disadvantage and social exclusion (Lucas, 2012; Delbosc and Currie, 2011) have established that socially disadvantaged groups in society have lower levels of car ownership and access to public transport, travel shorter distances and are less frequently engaged in social, cultural and economic activities (Scheiner et al. 2012).

Based on a survey in Australia, Delbosc and Currie (2011) conclude that lack of transportation options and the associated lower participation in activities has a negative impact on subjective well-being.

2.2 Second order relationships

In addition to these often studied first order relationships between travel behaviour and health several second order relationships also exist, as shown in Figure 1:

- Socio-economic and demographic characteristics and travel behaviour (arrows 5, 6, 7)
- Physical activity: walking and cycling versus wider activity patterns (arrow 8)
- Subjective well-being and the use of active modes (arrow 10)
- Self-selection effects (arrows 5 and 9)
- Macro-micro effects and social influence (no specific arrow)

Socio-economic and demographic variables (arrows 5, 6, 7)

The importance of socio-economic and demographic variables such as age, gender, education level and household characteristics for travel behaviour (arrow 5) is generally recognized. For instance, Stipdonk et al. (2013) discuss how total travel distance depends on age, and how this has changed over recent decades in the Netherlands. Also gender effects on e.g. travel mode choice have been widely documented (e.g. Matthies et al., 2002). In addition, demographic variables can also influence the impact of physical activity, the air pollution intake, and crashes/falls on health. In other words, an effect modification effect can exist, as conceptualized explicitly by arrow 6. For example, a fall from a bicycle may have more impact on someone who is 80 years old than on a 15 year old. As another example, Beelen et al. (2008) show that differences exist in the relative risks of mortality and hospitalisation due to traffic-related black carbon concentrations between men and women, age groups and socio-economic status. With respect to differences in the health benefits of physical activity on health, Bauman (2004) mentions that individuals with overweight and diabetes will profit even more from physical activity engagement than other groups. These moderating effects have been studied much less than the aggregate health effects. As the examples above show, the effects are not always straightforward and may depend on an individual's baseline situation. The effects may also be confounded with other socio-economic or demographic factors. For instance, smoking behaviour has been found to influence the relative risk of lung cancer and respiratory problems when exposed to black carbon, but smoking behaviour also differs between socio-economic classes

(Reid et al., 2010). Finally, we note that the effects of socio-demographic characteristics on different travel-related health outcomes may be contradictory. For instance, whereas the elderly may benefit the most from physical activities such as cycling, they are also more vulnerable to crashes/falls (and will be more seriously injured) and more sensitive to pollution.

Note that personal characteristics can also influence non-travel related physical activity (arrow 7) and its impact on health, as well as the impact of wellbeing on health.

Interaction of travel-related physical activity and other physical activity (arrow 8)

It is important to remember that walking and cycling are not the only forms of physical activity (Figure 1). People may therefore substitute cycling for other physical activities. This will reduce the additional health benefits of cycling. On the other hand, people who cycle may feel fitter, and may therefore engage in more physical activity. We hypothesize that both effects occur, but probably for different (groups of) people.

The scarce findings regarding the relationship between total physical activity and travel-related physical activity (PA) differ. Forsyth et al. (2008) and Troped et al. (2010) report that differences in spatial setting have an impact on the amount of transportation and leisure walking but that overall physical activity is not affected. This would suggest that increases in travel-related PA, caused by urban design or interventions, will substitute other forms of PA. A recent study by Brown et al. (2015) suggests that the introduction of a light rail system in Salt Lake City has led to more physical activity in access and egress travel, which also leads to a higher total level of PA. Saelens et al. (2014:854) found that "transit users had more daily overall physical activity and more total walking than did non-transit users but did not differ on either non–transit-related walking or non-walking physical activity." Clearly, more research is needed to disentangle the relationship between travel related and other forms of physical activity. From a policy point of view, the crucial issue is to what extent an increase in transportation walking or cycling related PA, brought about by a policy intervention, is compensated by a reduction of PA in other domains. Longitudinal studies are needed to provide a definitive answer to this issue.

Causality of subjective well-being and the use of active modes (arrow 10)

We argue that it could very well be that people with a relatively high level of subjective well-being are more likely to use active modes (arrow 10). However, to the best of our knowledge this potential relationship has not yet been investigated. Spinney et al. (2010) found a positive association between self-reported subjective well-being and physical activity for elderly people, although without explicitly stating the direction of causality. Most studies focus on reverse causality: the impact of physical activity on mood and mental health (e.g. Wood et al., 2013; Paluska, Schwenk 2000). Other studies, however, find evidence of the relationship. In a longitudinal study, Baruth et al. (2010) found that those who indicated higher levels of subjective well-being were more likely to increase PA levels in an intervention programme. Studies based on self-determination theory (SDT) (e.g. Standage et al., 2012) suggest that the causality might work both ways. Those who are intrinsically motivated to engage in PA, because they enjoy specific forms of PA, will show higher levels of PA, but also better mood due to PA, which in turn reinforces intrinsic motivation. The causality is thus likely to be bi-directional. Ignoring this bi-directional causality would lead to an overestimation of the impact of the use of active modes on subjective well-being.

Self-selection effects (arrows 5 and 9)

In addition to the discussion on causality above we add confounding: those related to self-selection effects. People often self-select in several respects. In the area of travel behaviour there is an increasing body of literature in the area of the impact of attitudes on mode choice (arrow 5) and of attitudes on residential self-selection (arrow 9). This literature first of all recognizes the importance of socio-economic and demographic variables. In this discussion we ignore this type of self-selection because it is generally included in transportation studies. In addition to those variables several other forms of self-selection exist (van Wee, 2009). Here we limit ourselves to residential self-selection (RSS). We first discuss RSS based on attitudes. Regardless of income, age etc. people with a pro-environmental attitude, or who like travelling by active modes, may self-select residential areas that support the use of these modes. See Cao et al. (2009) for an overview of the empirical literature in the area of residential self-selection. Such RSS effects are important for understanding the complex relationships between travel behaviour and health. Ettema and Nieuwenhuis (2015) found evidence that differences in the cycling frequency in different neighbourhoods were partly the result of the fact that households with a preference to cycle choose to live in areas that are more conducive to cycling.. Van Dyck et al. (2011), found that walking behaviour in different neighbourhoods in Ghent is primarily a function of neighbourhood walkability rather than determined by the fact that people who like to walk self-select them in walkable neighbourhoods. Handy et al. (2006) found that RSS only limitedly explains differences in walking across neighbourhoods in Northern California, but also note a substantial independent effect of the built environment on walking frequency. However, the literature regarding the effect of RSS in the context of walking and cycling is still limited, and more research in varying contexts would be needed to draw more definitive conclusions.

Another relevant form of RSS would be the extent to which health is a consideration for people when choosing where to live (not explicitly conceptualized in Figure 1). For instance, households may choose to live in locations where they are not exposed to pollutants of traffic or locations that offer good conditions for physical activity (e.g. walkable neighbourhoods). A preference to live in a neighbourhood with good conditions for physical activity can at least partly be the result of health related attitudes. Evidence of this type of self-selection is scarce and scattered. Studies of housing transactions (Wardman and Bristow, 2004; Van Praag and Baarsma, 2001) suggest that house prices are lower if houses are located in noisy areas, suggesting a preference for quieter locations. It should be noted, though, that prices are influenced more by the direct experience of noise than the indirect health effects of noise (e.g. hypertension). Similar effects have, however, been found in the context of air pollution (e.g. Anselin and De Gallo, 2006), suggesting that households self-select into healthier areas. Notably, this self-selection will depend on financial capacity, raising equity issues.

To conclude: ignoring self-selection effects may lead to incorrect results of research on the relationships between travel behaviour and health. In case of ignoring RSS this may easily lead to an overestimation of the magnitude of association between the built environment and physical activity, and next the positive related health effects of walking and cycling.

3. A research agenda

Our main recommendation is that because of the complex relations as conceptualized in Figure 1, it is important to at least be aware of those relationships, and in many cases to include those relationships in empirical research to disentangle the causal structure between (categories of) variables.

More specifically we think that there are several important research challenges in this area. As it is beyond the scope of this paper to present a more or less complete research agenda we propose a selection of topics resulting from discrepancies between the conceptual model and the academic literature published so far. We first discuss the challenges directly related to the conceptual model, followed by other challenges.

Conceptual model related challenges

A first challenge is to explore the combined effect of travel behaviour related determinants (physical activity, air pollution intake, collisions/falls and related casualties, and subjective well-being – blocks A, B, C and D in the conceptual model) on health. Some studies have assessed the total effect of e.g. a shift from car to bicycle by summing up the separate effects of each component on life expectancy (e.g., De Hartog et al., 2010; Rojas-Rueda et al., 2011), leading to the conclusion that the positive effects of physical activity outweigh the negative effects of casualties and the air pollution intake. However, studies measuring the combined effects on an individual level are still lacking, as are studies that identify the combined effect for specific population segments. We realize that such research is extremely difficult because of the complex causal relationships, and requires a huge data collection effort. Maybe combining all the effects in one study is too ambitious, and in one study only a selection of combined effects can be studied. Important research questions include: what is the combined effect of these determinants on health? How can policy measures improve the positive health effects of travel behaviour, addressing all four effects of blocks A, B, C and D?

A second challenge is exploring the interactions between travel-related physical activity and other physical activity, as conceptualized in the conceptual model by the bi-directional arrow of the blocks of travel related physical activity and non-travel related physical activity. Important research questions include: Are these forms of physical activity substitutes or complementary? For whom, and to what extent? What is the (additional) health impact of an increase in travel-related physical activity above and beyond other forms of physical activity?

Third, in addition to studying the impact of socio-economic and demographic variables on travel behaviour and health, the importance of attitudes and attitude formation, specifically in the area of health-related attitudes and self-selection processes related to travel behaviour is an important research topic; this relationship is conceptualized via arrows 5 and 9 in the conceptual model. The empirical knowledge base regarding residential self-selection in the context of walking and cycling is still limited and more comparative studies would be most beneficial. In addition, little is known about the extent to which health considerations play a role when deciding where to live and what effect this has on travel behaviour and health outcomes. Important questions include: How important are health-related attitudes for travel choices? To what extent do people self-select in neighbourhoods because of these attitudes? To what extent does a mismatch between preferred and actual neighbourhood characteristics exist, as far as health-related attitudes and travel behaviour are concerned? What are the implications of attitude formation and residential self-selection for the effects of policy interventions?

Other challenges

Fourthly, we argue that it is important to explore the impact of cycling levels on risks, because risks seem to be associated with cycling levels (see above). However the research in this area is limited, and so the relationship between cycling levels and risks is as yet unclear. This relationship may well be context specific, partly depending on the policies aimed at increasing cycling levels. For example, policy makers may decide to develop more and safer cycling infrastructure to increase cycling levels. If improved cycling facilities lead to higher cycling levels (Reynolds et al., 2009), and to lower risks, it is difficult to tell whether the safer cycling infrastructure or the larger number of cyclists is responsible for the reduced risk. A study by Robinson (2005) indicated that a reduction in cycling levels, brought about by the introduction of compulsory helmets, led to an increase in the risk per cycling kilometre of injury and fatality, suggesting an autonomous safety-in-numbers effect. However, more research is needed to disentangle the effects of numbers and infrastructure on safety. The overarching research question is: Which relationships exist between cycling levels and risk, and which factors influence these relationships?

Fifthly, we think it is important to study the relevance of adoption phase related self-selection effects with respect to cycling. Maybe the pioneers, the people who are the first to start cycling in a city or town, are a specific group of individuals, with other characteristics and travel behaviour (including cycling behaviour) than people who follow later. Consequently, the related health effects can differ between those groups. Also, early adopters of cycling may respond in a different way to the built environment and may experience different barriers to cycling compared with later adopters. Important research questions include: which groups of cyclists can be distinguished in a specific area? To what extent do such self-selection effects exist? What is the importance of these self-selection effects for the impact of travel behaviour in general and cycling in particular, on health-related outcomes?

A sixth challenge relates to transport innovations. This firstly relates to incremental innovations in current vehicles or other parts of the transport system, examples being cleaner and safer road vehicles. It secondly relates to more radical innovations such as e-bikes or autonomous vehicles. It is important to know how such innovations influence travel behaviour, but also how they influence health in the context of their implications for physical activity, exposure (and contribution to pollution), safety and effects on mood and subjective well-being. Important research questions include: Which transport innovations might be expected in the coming decades? How will these influence travel behaviour and related health effects, in which contexts?

In addition to these content-related challenges, a final challenge relates to research methods. A general rule of thumb is that more complex causal structures need more complex statistical methods, and this also applies to the research topic of this paper. We therefore recommend the use of advanced research methods, such as Structural Equation Models (SEM), over simple methods, such as multivariate regression models, to disentangle the complex causalities as conceptualized in the conceptual model. In addition, to disentangle causalities (such as the impact of an increase in travel-related PA on other forms of PA) we advocate the use of longitudinal research designs. In particular, measurements before and after policy interventions will be most useful to better disentangle the causalities discussed in this paper.

4. Conclusions

Because of the complex relationship between the variables in Figure 1, research that ignores this complexity might easily draw the 'wrong' conclusions. We argue that research into the area of health and travel should at least make the conceptual structure of variables (not) included explicit, and preferably discuss the importance of not including important relationships. The complex nature of the links between travel and health suggest that researchers should consider advanced research methods.

Secondly we conclude that the relationships between travel behaviour and health are still poorly understood, and consequently much additional research is needed. Important topics include the interactions between travel behaviour and other physical activity, the complex relationship between cycling and health, and self-selection effects.

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