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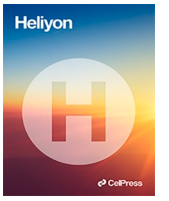

Review article

Effectiveness of nudges for sustainable transportation: A systematic review

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ABSTRACT

Behavior changes in the transportation sector are crucial for mitigating climate change. However, previous studies have not specifically reviewed the literature on nudging from the perspective of enhancing sustainable transport. Therefore, the objective of this systematic review is to assess whether nudge interventions are effective in fostering a transition toward more sustainable transport behaviors. A systematic data search was conducted using the Web of Science, Academic Search Premier, SocINDEX, and PsycINFO. The inclusion of articles was restricted to peer-reviewed scientific articles published in English. The selected criteria were as follows: (i) nudge intervention targeting transport behavior with the aim of lowering transport emissions, (ii) sample measurements before and after the intervention where applicable or had a continuous behavioral measurement, and (iii) the change in behavior was measured. Seventeen articles comprising 23 studies met the inclusion criteria. Sample sizes varied between 8 and 54,889. Risk of bias was assessed using the Joanna Briggs Institute's (JBI) critical appraisal tool. Relevant data from the studies were gathered into a working table that served as the basis for synthesizing the results. The nudge interventions varied considerably, and behavior was measured using different subjective and objective methods. Behavioral changes were observed in most studies (14/23). Thus, this review provides tentative evidence that nudge interventions can decrease car use and increase the use of sustainable travel modes and driving behaviors. No systematic patterns were found regarding the effectiveness of certain types of nudges or use of multiple nudges. One critical conclusion for future directions was the need of methodological and theoretical unification to gain a better understanding of the viability of nudges to alter transportation behavior.

1. Introduction

Sustainable transportation is key for mitigating greenhouse gas (GHG) emissions. Transport is an important part of the United Nations Agenda 2030 and its 17 sustainable development goals (SDGs) [1]. Despite technological advances, compared to the 1970s, GHG emissions have more than doubled [2]. In 2019, transportation contributed to approximately one-quarter of the global energy sector's GHG emissions [3]. In Europe, 82 % of transportation emissions are from road transport, half of which are from private car use

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[4]. Given the high share of emissions of private cars, changing driver behavior is one way to significantly reduce emissions.

Behavioral changes have been listed in the Intergovernmental Panel on Climate Change (IPCC) report as a means to reduce emissions in the transport sector [5]. Various factors can prevent individuals from making sustainable transportation choices in their lives; therefore, finding ways to make climate-friendly choices easier is important. Therefore, promoting climate-friendly behavior in transportation can be challenging because the behavior to be changed is currently widely accepted and is largely a norm in society. Since technological solutions alone have been unable to solve the problem and traditional social steering methods, such as raising taxes, pose a possible risk of increasing inequality, other methods for changing behavior are needed to complement these mitigation measures.

One form of behavioral change relates to choice architecture, modifying behavioral interventions and *nudges*, and how they can be used to mitigate transportation emissions. Nudges, introduced by Thaler and Sunstein [6], are appealing behavioral steering methods because they do not limit individuals' freedom of choice and are usually cost effective. In the past decade, several governments and policymakers worldwide have taken advantage of nudges in a variety of areas, from voluntary retirement savings to healthy behaviors. In a meta-analysis of different soft interventions to reduce car use, the researchers concluded that soft interventions could decrease car use by approximately 7 %; however, there was considerable variation in effectiveness based on the intervention type and targeted psychological variable [7]. However, to the best of our knowledge, previous studies have not specifically reviewed the literature from the viewpoint of sustainable transport.

1.1. Nudge

A "nudge" is defined as a deliberate alteration in choice architecture that influences people's behavior in a predictable way but preserves the possibility of choosing another option [6]. The use of significant economic incentives in steering decision-making is not considered a nudge. Nudges should be easy and inexpensive to avoid. Choice architecture refers to how decision-making situations are structured, and choices are presented. According to the nudge theory, changes in decision-making situations and environments affect behavior and the chosen options.

The meta-analytic evidence by Mertens et al. [8] suggests that choice architecture interventions have a small to medium effect size in promoting behavior change, albeit with significant variation due to, for example, the heterogeneity of interventions and contexts. To investigate the real-world scalability of nudge interventions, DellaVigna and Linos [9] conducted a meta-analysis examining only large-scale randomized controlled nudge interventions conducted by governmental nudge units, covering over 23 million people and arguably avoiding academic-publication bias. They found a significantly smaller, robust effect [9] More recently, a second-order meta-analysis on specifically climate behavior interventions by Bergquist et al. [10] found a stronger effect, but they too highlight the variability of behavioral interventions (including nudges) depending on the type and target of the intervention. Thus, the heterogeneity and contextual variety within nudge interventions place significant strain on the interpretability of the current meta-analytic findings. Together, these findings and critiques underscore the importance of exploring the qualitative aspects of nudges in a specific behavioral context to understand their effectiveness more clearly.

The nudge framework can be considered through a *dual process model of thinking* that suggests that information processing can be divided into two types: Systems 1 and 2, which produce fast and slow thinking [11]. The nudges exploiting System 1 are designed to preserve freedom of choice, but without much conscious deliberation. Graphic health warnings, default rules, and automatic enrollments are examples of System 1 nudges. They require little effort and time, and are designed to work automatically, for example, by inducing fear or hope. However, System 2 nudges require analytical thinking and are more energy consuming but emphasize agency and autonomy. The most typical example of a System 2 nudge is the disclosure of factual information such as statistics. People generally prefer System 2 nudges over System 1 nudges, but in some cases, when given information that System 1 nudges are more effective, attitudes shift more toward System 1 nudges, approximately 10 %–12 % [12].

Despite the use of the term nudge theory, it is noteworthy that the definition of nudging has been regarded as too broad and general to be called a theory and is better considered a general framework or an umbrella term for interventions aimed at changing behavior by altering the context [13]. Noteworthy is that unresolved questions remain that require further investigation. Among others, the definition of a nudge, its justification, and its effectiveness have prompted a wide debate. Several refinements have been introduced to the definition [14–16]. Nudges can be categorized in various ways, such as by type, mechanism of action, and/or structure [17–19]. In this review, we utilize a four-component nudge taxonomy based on the Nuffield Ladder of Interventions [19]. This provides a pragmatic way to categorize transport interventions, even when they are not explicitly designed as nudges. This grouping is also one of the earliest attempts to categorize various nudges and as such, can be found in the background of a variety of nudge literature [20,21]. The following categorization of nudges is proposed.

1) Provision of information,
2) changes to the physical environment,
3) changes to the default policy, and
4) use of social norms and salience.

This review focuses on studies that use nudging. However, such an approach is sometimes used without explicitly referring to the word *nudge*. Several other theoretical frameworks for behavioral change were used in the intervention studies included in this review, although their interventions could also be defined as nudges. These theories have been used as tools to design interventions and pre- and post-surveys to examine the process of behavioral change. In this systematic review, we used nudge theory as our framework;

however, in our literature search, we also considered studies that did not define their intervention as a nudge, even though it fulfilled the definition of a nudge, regardless of the theoretical framing used in those articles.

1.2. Research motivation and aims

Interest in utilizing behavioral methodology to advance sustainable transport is increasing, but no literature review exists of nudges in sustainable transportation, despite high hopes placed on behavioral change as one of the means to reduce emissions in the transportation sector [22]. Thus, a systematic review is urgently needed to promote the design of effective nudge interventions to mitigate climate change. This systematic review was conducted to bridge the gap in the need for a comprehensive understanding of nudges implemented in the transportation sector and their effectiveness. The aim was to provide knowledge about the potential of nudges in promoting sustainable transport behavior, including travel-mode choice, driving planning, and driving habits.

Our research questions are.

1. Are nudges effective in inducing behavior change toward more sustainable transportation behavior?
2. What type of nudges are the most effective in inducing the behavior change toward more sustainable transportation behavior?

2. Methods and materials

This systematic review was conducted in line with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol; however, we did not preregister the review. Efforts were made to reduce potential bias in selecting studies through thorough discussions among the group of researchers regarding the definition of nudges and setting inclusion and exclusion criteria. Although the definition of a nudge is ambiguous, we attempted to minimize ambiguity in the inclusion criteria. We also attempted to avoid spectrum bias regarding the target groups by including all possible populations, both children and adults.

2.1. Information sources and search strategy

Data for this systematic literature review on sustainable transport choices utilizing the nudge methodology were collected from four databases: Web of Science, Academic Search Premier, SocINDEX, and PsycINFO. The first search was conducted between February 17 and February 19, 2021, and a supplementary search was conducted on January 20, 2022. The search terms used are listed in Table 1.

2.2. Selection process

The selection process is illustrated in Fig. 1. Studies were reviewed at each stage using the Rayyan program [23]. At least two reviewers reviewed each article. Eleven researchers participated in the review at different stages. The research team discussed conflicts in the review and a joint decision was made regarding inclusion. Where necessary, the inclusion criteria were refined to achieve a coherent set. The inclusion criteria were as follows.

Table 1
Search terms used in different databases. For SocINDEX and PsycINFO databases, the search term was supplemented by the databases' own subject headings. In all databases, the results were further restricted to scientific articles in English and the EBSCO platform databases used the "Apply equivalent subjects" extension.

Database	Search query
Academic Search Premier and Web of Science	(nudge OR nudging OR persuasion OR persuasive OR "choice architecture") AND (traffic OR mobility OR travel OR transport OR commute* OR transit OR "public transport" OR walking OR walk OR pedestrian OR bike OR bicycle OR cycling OR biking OR bus OR train OR tram OR subway OR metro OR underground OR tube OR car OR vehicle* OR driving OR drive OR carpool* OR "car pool*" OR "trip chain*" OR "car share*" OR parking)
PsycINFO	(nudge OR nudging OR persuasion OR persuasive OR "choice architecture" OR DE "Persuasion") AND (traffic OR mobility OR travel OR transport OR commute* OR transit OR "public transport" OR walking OR walk OR pedestrian OR bike OR bicycle OR cycling OR biking OR bus OR train OR tram OR subway OR metro OR underground OR tube OR car OR vehicle* OR driving OR drive OR carpool* OR "car pool*" OR "trip chain*" OR "car shar*" OR parking OR DE "Geographical Mobility" OR DE "Traveling" OR DE "Commuting (Travel)" OR DE "Pedestrians" OR DE "Transportation" OR DE "Ground Transportation" OR DE "Water Transportation" OR DE "Public Transportation" OR DE "Motor Vehicles" OR DE "Railroad Trains" OR DE "Automobiles")
SocINDEX	(nudge OR nudging OR persuasion OR persuasive OR "choice architecture" OR DE "PERSUASION (Psychology)") AND (traffic OR mobility OR travel OR transport OR commute* OR transit OR "public transport" OR walking OR walk OR pedestrian OR bike OR bicycle OR cycling OR biking OR bus OR train OR tram OR subway OR metro OR underground OR tube OR car OR vehicle* OR driving OR drive OR carpool* OR "car pool*" OR "trip chain*" OR "car shar*" OR parking OR DE "TRANSPORTATION" OR DE "COMMUTING" OR DE "URBAN transportation" OR DE "BICYCLE sharing programs" OR DE "CITY traffic" OR DE "MOTOR vehicles")

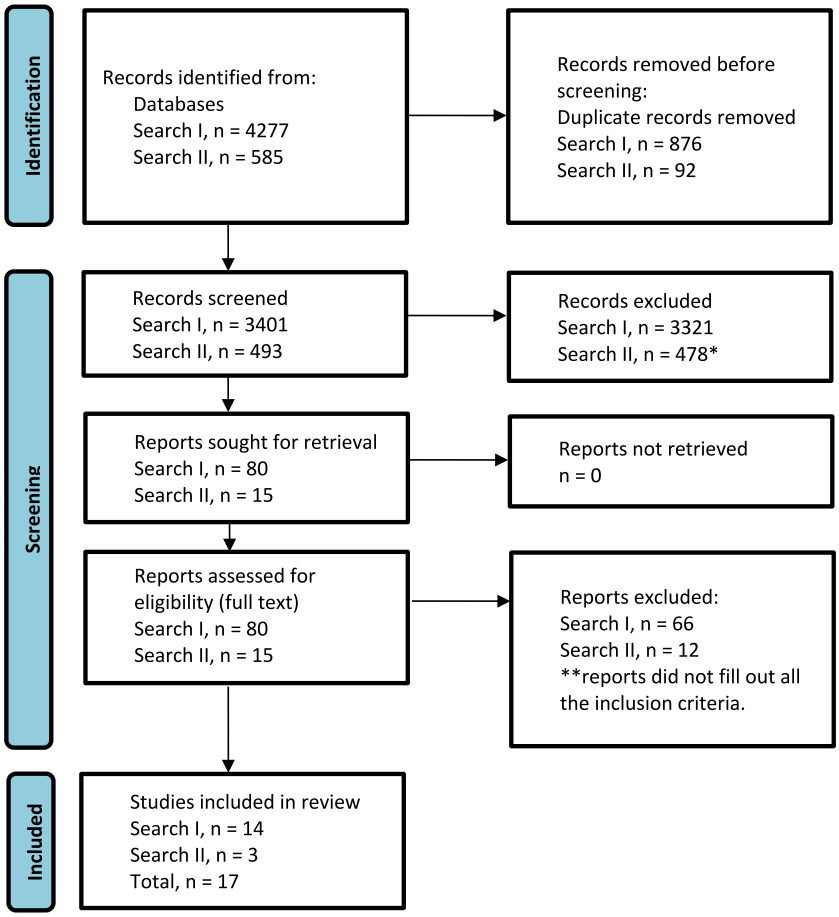

Fig. 1. Prisma flow diagram for systematic reviews
*At the evaluation stage, it was noted that one article had already been evaluated in the first round and was deleted from supplementary consideration.** T**he inclusion criteria**: 1) The study used a nudge intervention, even if this was not called a nudge in the study. A study was understood as nudging when it met one or more of the following four categories: provision of information, changes to the physical environment, changes to the default policy, and use of social norms and salience. 2) The interventions did not include major infrastructure projects such as building bike lanes. 3) The intervention was targeted at changing transport behavior by influencing either travel-mode choice, driving planning, or driving habits to reduce transport emissions. 4) Air traffic was not considered in this study. 5) The intervention was not aimed at reducing risky behaviors such as driving while drinking. 6) This study measured behaviors, not just intentions or attitudes. 7) The study included measurements obtained before and after the intervention. 8) The study was peer-reviewed and published in English in an international scientific journal.

1) The study used a nudge intervention even if it was not called a nudge. A study was understood as nudging when it met one or more of the following four categories: provision of information, changes to the physical environment, changes to the default policy, and use of social norms and salience.
2) The interventions did not include major infrastructure projects such as the building of bike lanes.
3) The intervention was targeted at changing transport behavior, by influencing either travel-mode choice, driving planning, or driving habits to reduce transport emissions.
4) The study did not concern air traffic.
5) The intervention was not aimed at reducing risky behavior such as drunken driving.
6) The study measured behavior, not just intention or attitude.
7) The study included measurements before and after the intervention where applicable, or had a continuous measurement of behavior, such as tracking with a mobile app or registering for a service.
8) The study was peer-reviewed and published in English in an international scientific journal. A control group was not required; however, studies that did or did not include a control group were analyzed separately.

2.3. Data collection process

To extract relevant information from all included articles, two researchers gathered information at a working table, cross-checked the gathered information, and had discussions with the rest of the research team to confirm all relevant aspects. The information

included the reference of the article, country and city in which the study was conducted, number of participants, size of the control group, type of intervention, nudge category, duration of the study, outcome variables, and the results of the study. If the study additionally addressed interventions or hypotheses not relevant to our research question, the information was excluded. The results were synthesized based on this information.

2.4. Risk of bias assessment

Risk of bias assessment for the included studies was conducted by two independent researchers using the Joanna Briggs Institute (JBI) Critical Appraisal Tool for quasi-experimental studies [24] (See Table 2). The initial interrater reliability was moderate (78 % agreement; Cohen's k = 0.52). After discussion, a complete agreement was achieved. Table 1 presents the collective conclusions of the bias evaluation. The included studies were heterogeneous in terms of risk of bias, ranging from 1/9 to 8/9. Because of unclear reporting in many of the included studies, several criteria could not be clearly determined.

Q1 = Is it clear in the study what is the "cause" and what is the "effect" (i.e., there is no confusion about which variable comes first)? Q2: Was there a control group? Q3 = Were the participants included in any similar comparisons? Q4 = Were the participants included in any comparisons receiving similar treatment/care other than the exposure or intervention of interest? Q5 = Were there multiple measurements of the outcome, both pre- and post-intervention, or exposure? Q6 = Were the outcomes of the participants included in any comparison measured similarly? Q7: Were the outcomes measured reliably? Q8 = Was the follow-up complete, and if not, were the differences between groups in terms of their follow-up adequately described and analyzed? Q9 = Was the appropriate statistical analysis used?

2.5. The research material

The final sample comprised 23 studies, reported in 17 articles. The publication year and number of articles are shown in Fig. 2. Articles that reported more than one study were divided into several rows. The studies were conducted in Italy (4), the United Kingdom (1), Austria (2), Denmark (1), Finland (2), Spain (2), Belgium (2), the Czech Republic (1), Germany (1), The Netherlands (1), Sweden (1), Switzerland (1), and the United States (1). Four studies were conducted in Europe; however, the countries of origin were not specified [25].

In nine studies, data were collected through self-reports such as questionnaires, travel diaries, or mobile applications [35,36,

Table 2
Quality analysis using Joanna Briggs Institute critical appraisal tools for quasi-experimental studies.

Author(s)	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Total
Controlled studies										
Beale & Bonsall (2007), Experiment 1	YES	YES	UNCLEAR	YES	YES	YES	UNCLEAR	NO	NO	5/9
Beale & Bonsall (2007), Experiment 2	YES	YES	YES	YES	YES	YES	UNCLEAR	NO	NO	6/9
Arroyo et al. (2018)	YES	YES	UNCLEAR	UNCLEAR	YES	YES	UNCLEAR	NO	YES	5/9
Lieberoth et al. (2018)	YES	YES	NO	YES	NO	YES	YES	UNCLEAR	NO	5/9
Cellina et al. (2019)	YES	YES	UNCLEAR	YES	YES	YES	UNCLEAR	UNCLEAR	NO	5/9
Ahmed et al. (2020)	YES	YES	UNCLEAR	YES	YES	YES	UNCLEAR	NO	YES	6/9
Kristal & Whillans (2020), Experiment 1	YES	YES	UNCLEAR	YES	NO	YES	YES	YES	YES	7/9
Kristal & Whillans (2020), Experiment 2	YES	YES	UNCLEAR	YES	NO	UNCLEAR	UNCLEAR	YES	YES	5/9
Kristal & Whillans (2020), Experiment 3	NO	YES	UNCLEAR	NO	NO	YES	YES	YES	YES	5/9
Kristal & Whillans (2020), Experiment 4	YES	YES	UNCLEAR	YES	YES	YES	YES	YES	YES	8/9
Máca et al. (2020)	YES	YES	UNCLEAR	YES	NO	YES	UNCLEAR	NO	NO	4/9
Rosenfield et al. (2020)	YES	YES	YES	YES	YES	YES	YES	NO	YES	8/9
Uncontrolled studies										
Riener (2012)	YES	NO	YES	YES	YES	YES	YES	YES	NO	7/9
Bothos et al. (2014)	UNCLEAR	NO	YES	UNCLEAR	YES	YES	UNCLEAR	NO	NO	3/9
Gabrielli et al. (2014), Experiment 1	YES	NO	YES	UNCLEAR	YES	YES	UNCLEAR	YES	NO	5/9
Gabrielli et al. (2014), Experiment 2	UNCLEAR	NO	UNCLEAR	UNCLEAR	UNCLEAR	UNCLEAR	UNCLEAR	YES	NO	1/9
Gabrielli et al. (2014), Experiment 3	YES	NO	YES	UNCLEAR	YES	YES	UNCLEAR	NO	NO	4/9
Günther et al. (2020)	NO	NO	NO	NO	YES	YES	YES	UNCLEAR	YES	4/9
Van de Sompel et al. (2020)	YES	NO	NO	YES	YES	YES	NO	YES	YES	6/9
Khoshkangini et al. (2021)	YES	NO	UNCLEAR	UNCLEAR	YES	YES	YES	NO	NO	4/9
Sottile et al. (2021)	YES	NO	YES	UNCLEAR	YES	YES	YES	NO	NO	5/9
Ton & Duives (2021)	YES	NO	YES	YES	YES	YES	YES	NO	NO	6/9
Olsson et al. (2021)	YES	NO	UNCLEAR	YES	YES	YES	YES	NO	NO	5/9

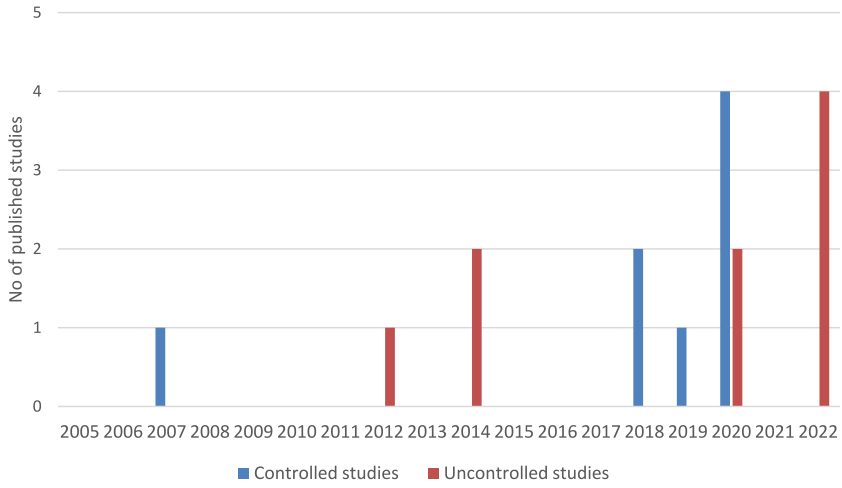

Fig. 2. Number of published articles by year.

38–41]. Seven studies relied on digital data, such as automatic journey tracking, travel-card usage, and fuel and other energy consumption while driving [25,27,28,31,34]. Seven studies used a combination of self-report and digital data [25,26,29,30,32,33,37]. Overall, the objectives of the studies were heterogeneous. Nevertheless, the studies aimed at shifting from private cars to more ecological modes of transport or increasing public transport use, economical and sustainable driving habits, car sharing, or cycling.

Categorizing the interventions strictly into four types turned out to be challenging because many interventions used several nudge types and thus could have fallen into more than one category. However, most interventions fall into only two of the four nudge categories: information sharing, utilization of social norms, or both. Changes in the physical environment were used in two studies [31, 41], combined with information from one study [40], and combined with both information and social norms in two studies [25,29]. One study combined information sharing with default suggestions in a route-planning application [26]. Frequently used nudge types include information campaigns and route-planning sites or applications, several of which exploited gamification.

3. Results

This section summarizes the main findings and research materials. We present the results in Sections 3.2 and 3.3 separately for studies that included a control group and those without a control group, respectively. The details of all the studies are presented in Tables 3 and 4. We first introduce the controlled studies (Section 3.1) and review the articles by nudge type. Next, we introduce uncontrolled studies (3.2) and examine them by nudge type.

Overall, considerable variations were observed in the methods and results. Moreover, the effect sizes were not reported in many of the studies, which made a numerical comparison impossible. Objective data were used in nine articles to study the impact of the nudge (or 14/12 studies in 9/11 articles) [25–33].

Only four studies using objective measures reported that nudges had any impact on mobility [27,28,31,33]. In two studies, the use of public transport increased. In the first uncontrolled study, a small increase was observed after receiving personalized travel plans in a mobile application [33]. In the second controlled study, participants in the control group and all the intervention groups were given free bus cards, encouraging messages, and personalized feedback [29]. The nudging elements used in the intervention groups were social rewards, gaming, and framing with information on the health benefits of sustainable traveling. However, since all groups increased their bus use, it seems that the key to behavioral change was a combination of a financial reward (free bus card) and nudging by encouraging messages and personalized feedback, not social rewards, gaming, or framing.

A combination of different elements was found to be effective in another study using objective outcomes without a control group [27]. However, in their study, elements were added as the intervention progressed. To decrease energy consumption when driving battery electric vehicles, the first condition of providing feedback alone produced no effect, but adding gamification and financial incentives helped. However, the results may reflect a longer-term learning curve or habit formation, instead of the failure of mere feedback to influence behavior. The fourth study to report positive results with objective measures (reduced fuel consumption) targeted an economic driving style using a vibrating safety belt for feedback [31].

3.1. *Controlled studies*

Twelve controlled studies reported in eight articles were included in this review. Five of the 12 studies targeting ecological transportation behavior reported positive effects [34–37]. However, none of these studies observed the effect systematically in all subgroups or analyzed variables. Four controlled experiments using objective measures did not find a statistically significant effect of nudges on changing travel behavior [25]. Descriptions of the studies and nudges used are presented in Table 3.

Table 3
Controlled studies.

Author (year)	Country	Data	Nudge aim	Nudge type (House of lords)	Measures	Outcome variable	Statistically significant results	Nudge description	Results, description[b]
Beale & Bonsall (2007) Experiment 1	UK	• Control group n = 102 •F020 Intervention group n = 103 Drop out: 50 %	Increase bus use.	Information Social	Subjective	Retrospective self-reported change in the bus use habits.	No[a]	Information leaflet via mail which corrected misconceptions considering bus use and contained information about the timetables.	• Both intervention & control group reported decrease in the bus use after intervention (19 % and 16 %, respectively). • Intervention mitigated the decrease marginally on women and on those who either had a positive attitude toward buses or who habitually or occasionally used the bus. • No statistically significant differences were found in the bus use habits.
Beale & Bonsall (2007) Experiment 2	UK	• Control group n = 23 • Intervention group 1. (leaflet + free bus ticket) n = 23 • Intervention group 2. (leaflet) n = 25 Drop out: 16 %	Increase bus use.	Information	Subjective	Retrospective self-reported change in bus use habits.	Yes	Information leaflet via mail targeted to people who sometimes already used the bus. The leaflet corrected misconceptions considering bus use considering the characteristics of the target group.	• The information leaflet had a positive effect on bus use for males ($X2 = 4.20$, $df = 1$, $p < 0.05$), recent bus users ($X2 = 8.21$, $df = 1$, $p < 0.01$) and less on frequent travelers, those positively disposed to buses or over 45-year-olds in short term. It had a negative effect for females and 46–60-year-olds in the longer term. • The leaflet-and-ticket combination had a positive effect on bus use on those positively disposed to buses ($X2 = 3.77$, $df = 1$, $p < 0.05$) and recent bus users ($X2 = 4.81$, $df = 1$, $p < 0.05$) in short term, and for all respondents in long term.

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Table 3 (*continued*)

Author (year)	Country	Data	Nudge aim	Nudge type (House of lords)	Measures	Outcome variable	Statistically significant results	Nudge description	Results, description[b]
Arroyo et al. (2018)	Spain	• Control group n = 45 • Intervention group n = 73 Drop out: 76 % of those who originally agreed to participate.	Reduce private car use.	Information Social	Subjective	Self-reported daily amount of time spent traveling by private car in comparison to the total amount of time spent on transportation.	Not reported[a]	At least two of the following: 1. personalized information leaflet via mail about ecological travel modes and route options, 2. attendance at a talk given by an authority figure 3. watching a video of street interviews of people who have recently reduced their car use.	Private car use decreased 10.7 % in intervention group measured in daily travel time. The effectiveness of the intervention seemed to be highest on afternoon trips and when the trip was conducted solo or with family members.
Lieberoth et al. (2018)	Denmark	• Control group n = 29 • Intervention group 1. (nudge) n = 74 • Intervention group 2. (gamification) n = 69 • Intervention group 3. (health framing) n = 110 Drop out: not reported	Increase bus travel.	Physical Social Information	Subjective & objective	The number of trips by bus is measured by the usage of the travel cards and self-reports.	No	All groups (including control) received a free 4-week travel card and access to personalized feedback. • Nudge group was encouraged to plan their travels using a calendar provided by the research group, pre-commit to their plan by writing a letter to their future self and putting them in a visible place in their home. They also gained access to a Facebook group, where they could discuss their travel habits. • Gamification group could gain prices depending on their behavior. • Health frame group received information and feedback on the effects of exercise on their health.	There was no difference between the groups in travel cards usage ($H(3) = 3.82, p = 0.28$) or in self-reported changes in bus commute ($H(3) = 6.33$, $p = 0.098$).
Cellina et al. (2019)	Switzerland	• Control group n = 18/16 • Intervention group 1. (Ticino) n = 21 • Intervention group 2. (Zürich) n = 13 • Note: different N reported in different parts of the article. Drop out: 75 %	Reduce private driving and increase the use of public transportation & active travel modes.	Information Social	Unclear	The change in the average gCO_2/km & kWh/km detected by the app and confirmed by the participant.	Yes	GoEco! -mobile application offering travel plan options used persuasion tactics of feedback, goal setting, social comparison and gamification elements.	• CO_2 emissions and energy consumption declined in both study locations when only systematic (home-to-home) loops were considered. • The change was statistically significant in Ticino ($p < 0.05$), which is highly car-dependent area, but not in Zürich. • Average CO2 emissions declined in Ticino and increased in Zürich. However, these results were not statistically significant.

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Table 3 (*continued*)

Author (year)	Country	Data	Nudge aim	Nudge type (House of lords)	Measures	Outcome variable	Statistically significant results	Nudge description	Results, description[b]
Ahmed et al. (2020)	Belgium	• Control group n = 40 • Intervention group n = 12 Drop out: 13 %.	Decrease private car use and increase the use of active travel modes and public transportation.	Information Social	Unclear	GPS based travel distance traveled by public transportation and by active travel modes compared to total traveled distance.	Yes	Personalized travel plan (PTP) intervention in an online format utilized persuasion principles of reciprocation, consistency and commitment, liking, social proof & scarcity. Participants were offered information, feedback, social comparison, PTPs and asked for a commitment.	• Private car use of the intervention group decreased ($p = 0.046$, $d = 0.28$) and using of active travel modes increased ($p = 0.004$, $d = 0.45$). • No significant change in the use of public transportation. • PTP intervention seemed to trigger individual transitions mainly toward more action-oriented stages in the behavioral change process.
Kristal & Whillans (2020) Experiment 1	Europe	• Control group n = 39 900 • Intervention group n = 14 987 • Note: Subjects were unaware of the experiment. Drop out:	Increase car sharing.	Information Physical Social Norms salience	Objective	Registering for the car-sharing service	Yes[c]	Three different information letters: • Control group: no letter. • 1: treatment group: a standard letter containing information about a car-sharing service previously offered by their workplace. • 2. treatment group: a letter including the direct link to a car-sharing register form. • 3. treatment group: two peer testimonials with pictures of the peers.	Intervention group was more likely than the control group to register for the car-sharing service ($p < 0.001$). The effect was minimal ($d = 0.055$, 95 % CI [0.04, 0.07]). There was no difference between the letters.
Kristal & Whillans (2020) Experiment 2	Europe	N = 928 • Control and two treatment groups. • Note: Subjects were unaware of the experiment. • The size of the control group was not reported. Drop out:	Increase car sharing.	Information salience	Objective	Activation in the car-sharing service, opening a link to the service	No	Two intervention letters and a control email. The first treatment email provided "car-sharing matches" and the second treatment email provided matches and a reminder of financial benefits of car-sharing.	• The intervention had no effect on service activation ($p = 0.746$, $d = 0.00$, 95 % CI [−0.15, 0.15]). • The percentage of participants who clicked the link did not differ between conditions ($p = 0.939$, $\eta 2 = 0.00$, 95 % CI [−0.002, 0.006]). • The effect of the intervention emails compared to the control letter was zero. ($t(599) = 0.324$, $P = 0.746$, $d = 0.00$, 95 % CI [−0.15,0.15]).

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Table 3 (*continued*)

Author (year)	Country	Data	Nudge aim	Nudge type (House of lords)	Measures	Outcome variable	Statistically significant results	Nudge description	Results, description[b]
Kristal & Whillans (2020) Experiment 3	Europe	N = 2468 • Control group was reported to be half of the participants • Note: Subjects were unaware of the experiment. Drop out:	Nudge aimed to increase bus use.	Information salience	Objective	Purchase of bus card	No	Email using loss-aversion, highlighting lost money when the subject had not taken advantage of the free bus journeys previously offered to them.	The message had no effect on purchases of bus cards and the effect size was equal to zero (p = 0.797, d = −0.01, 95 % CI [−0.06, 0.05]).
Kristal & Whillans (2020) Experiment 4	Europe	N = 1095 • Note: Subjects were unaware of the experiment. The size of the control group was not reported. Drop out:	Nudge aimed to reduce private car use and increase more sustainable travel options.	Information	Subjective & objective	Self-reported difference in private car use (1–5) during the previous five days compared to the baseline survey, car-sharing service registrations and discounted travel product purchases	No	PTP emailed to participants to reduce private car trips. Contained information about alternative modes of travel, car-sharing matches, public transport timetables, bike routes, and discounts.	• Private car use did not change after intervention (p = 0.992, d = 0.01, 95 % CI [−0.13, 0.14]). • No significant effect on register for the service or product purchases.
(Máca et al., 2020)	Czech Republic	N = 482 • Control group • Intervention group 1. (Social gamification) • Intervention group 2. (Social gamification + financial reward - flat rate) • Intervention group 3. (Financial reward - flat rate) • Intervention group 4. (Financial reward - decreasing rate) • Note: group sizes were not reported Drop out: 65 % of those who initially agreed to participate.	Nudge aimed to increase commuter cycling	Social	Subjective & objective	The number of work or school journeys by cycling recorded by the participant.	No	Cyclers application used social gamification (nudge) and financial incentives.	• Social gamification (nudge) did not affect the amount of cycling. • The social gamification combined with financial incentives (p < 0.01) did increase cycling.
Rosenfield et al. (2020)	USA	• Control group n = 494 • Intervention group 1. (information/nudge) n = 481 • Intervention group 2. (rewards) n = 489	Nudge aimed to decrease private car commute.	Information	Subjective & objective	The frequency of using the car park and the use of the travel cards measured passively, and self-reported behavior change.	No	Information campaign by email; including messages about the benefits of decreasing car use and common misconceptions.	• Decrease in car park use was observed in all groups, but no significant differences were found in treatment groups compared to the control.

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Table 3 (*continued*)

Author (year)	Country	Data	Nudge aim	Nudge type (House of lords)	Measures	Outcome variable	Statistically significant results	Nudge description	Results, description[b]
		• Intervention group 3. (Both) n = 503 Drop out: 3 % opted out of the research. Of those 40 %–60 % opened multiple informational emails and 37 % completed an exit survey.							• The survey results overstated the behavior changes compared to passive travel data.

[a] The study did not report a statistically significant change, but reported that nudging produced some change.
[b] Results descriptions are reported with the amount of detail allowed by the original articles.
[c] Statistically significant change was observed, but the effect was so small that it can be considered not having an effect.

3.1.1. Information campaigns

In a study by Arroyo et al. [35], private motoring was reduced by nudge interventions addressing different types of barriers to action using persuasion tactics of reciprocity and scarcity, authority, social proof, and liking on habitual drivers. Adjusted regression models indicated that participants traveling alone or with a member of their household were more positively influenced by the intervention than those traveling with other people, suggesting that travel-mode decisions may be more rigid for less familiar people. In addition, participants traveling in the afternoon were more positively affected than those traveling in the morning, evening, or night. The researchers assumed that activities are more flexible in the afternoon than in the morning, whereas in the evening and night, travel modes other than private cars may not be possible, for example, because of reduced availability.

Beale and Bonsall [36] conducted two separate information campaigns to promote public transportation. Both campaigns positively affected some participants. In the first experiment, an information leaflet containing timetables and route information debunking myths about bus travel was sent to the intervention group. During the experiment, bus travel decreased in both the control and intervention groups based on self-reports. However, the intervention mitigated the decrease in bus travel among women and those who had already occasionally used the bus or had a positive attitude toward bus travel. The leaflet had a picture of a female, which, according to researchers, may have caused the leaflet to be more efficient for women.

Second, the revised experiment targeted only people who used the bus occasionally and considered the bus to be their second choice. Researchers modified the leaflet to make it more reliable for male participants and car owners. A condition in which the participant received a leaflet and a free bus ticket was also added to the experiment. In this study, the intervention increased men's self-reported bus traveling. For females, the intervention negatively affected their bus travel. Interestingly, receiving only a leaflet had a stronger positive effect on males and people aged >60 years than the condition in which participants also received a free ticket.

Rosenfield et al. [32] found that an informational message campaign also decreased the use of car parks and increased the use of public transport. However, the effect was only observed in survey responses after the intervention and not in passively collected data on actual behavior during the intervention. In the study, participants were divided into three intervention groups in addition to the control group and received 1) weekly informational emails about the benefits of reducing private motoring, 2) a small financial reward for not using the car park, and 3) a combination of information and reward. All groups decreased their use of car parks during the 6-week campaign. The decrease was slightly larger in the intervention group than in the control group and was largest with the combination intervention.

Kristal and Whillans [25] tested nudges using well-powered experiments, but none increased sustainable traveling. Two of the experiments aimed to increase carpooling through information messages, but produced no effect on travel behavior based on data from the carpooling-service system. Although the result of the first study, to get users to sign up for the service first, was statistically significant, the effect was minimal ($d = 0.055$); therefore, the intervention cannot be considered to have an actual impact. The third study aimed to increase the purchase of bus cards using an information message, and the fourth study provided participants with an individualized travel plan and information on alternative modes of travel to reduce private car use without success. Thus, three experiments encouraged carpooling, and one promoted bus use. However, they may not have been attractive alternatives in this study because they were conducted with participants working at an airport outside a major European city.

In a study by Lieberoth et al. [29], behavioral interventions lasting four weeks were used to increase bus use. The interventions included a nudge involving pre-commitment, gamification, and a health perspective, in which information and feedback were offered. However, the control group was given a free bus card, an encouraging message, and access to a website that provided personalized feedback. The experimental groups differed from the control group mainly in terms of whether nudging elements (such as social rewards), gaming elements, or health benefits were emphasized. No statistically significant differences were found between the groups measured electronically using travel-card swipes. Measured by other indicators (intention to renew the travel card and number of logins to the website), the gamification group showed the most promise.

3.1.2. Route-planning applications

Two small studies utilized route-planning applications based on the provision of information, although they included other behavior steering methods, such as financial incentives or rewards [34,37].

Ahmed et al. [34] studied an individually tailored route-planning application that informed the participants about their GHG emissions, increased the physical activity level of traveling, and decreased car dependency; however, the public transport occupancy rate did not change.

Another application by Cellina et al. [37] aimed to reduce private driving in two areas: Ticino and Zürich. The application offered alternative travel plan options, feedback, reminders, and rewards but required a considerable amount of reporting from the participants about their journeys, which led to a 75 % dropout rate from the 576 individuals who entered the study. CO_2 emissions and energy consumption were reduced in home-to-home loops during the 4-week intervention, but this association reached statistical significance only in Ticino. As the researcher suggested, in Zürich, the use of public transportation is already common, and little room is left for increasing its use, whereas Ticino is a highly car-dependent area and less public transportation is available. For the other journeys, no statistically significant changes were observed using automatically collected data from the application.

In a study by Máca et al. [30], financial rewards seemed to be more beneficial than social gamification for commuter cycling. Social gamification did not affect the amount of cycling unless combined with financial incentives. Social gamification comprises scoreboards, challenges, the collection of points and badges, and personalized notifications. Although the analyses were based on passive data gathered via the application during the 4-week intervention, the study had a considerable dropout rate (65 %).

Table 4
Uncontrolled studies.

Author and year	Country	Data	Nudge aim	Nudge type	Measures	Outcome variable	Statistically significant results	Nudge description	Results[b]
Riener (2012)	Austria	N = 10 Drop out:	Reducing fuel consumption.	Physical	Objective	Driving economy (fuel consumption) compared to baseline test	Yes	A subliminal tactile stimulation via driver's seat (day 1) and vibrating safety belt (day 2).	• Statistically significant improvement in driving economy with subliminal feedback condition (safety belt) compared with the baseline (at $\alpha = 0.01$). • The driver's seat condition did not produce statistically significant improvement.
Bothos et al. (2014)	Austria	N = 24 Drop out: Dropout was not reported, although claimed to be low.	Decrease private car use and increase sustainable travel modes.	Information Default Physical	Subjective & objective	Self-reported behavioral change selecting travel modes and GPS logs	No report[a]	Travel planner applications contained several nudges, such as offering relevant information, setting default options and making the desired options more visible.	Self-reported measures indicated an increase in environmentally friendly travel routes, but the GPS logs did not indicate behavioral changes.
Gabrielli et al. (2014)	Italy	N = 8 Drop out:	Increase sustainable travel modes.	Information Social	Subjective	Self-reported use of travel modes	No report[a]	Mobile applications used goal setting, self-monitoring, personalized text messages and social comparison (leaderboard) to encourage sustainable mode choices.	The use of sustainable travel options increased 14 %.
Gabrielli et al. (2014)	Finland	N = 12 • Intervention group 1. (all the app features) n = 7 • Intervention group 2. (only visual feedback on emissions) n = 5 Drop out:	Decrease private car use and increase sustainable travel modes.	Information	Subjective	Self-reported number of trips with different travel modes, time spent traveling, and the distance traveled during the week	No	• Mobile app prototype featured automatic journey tracking, journey planner, trip history, visual feedback on CO2 emissions. • A set of challenges that aimed to motivate users to use sustainable transportation.	No statistically significant differences in CO_2 emissions were detected between the user groups.
Gabrielli et al. (2014)	Spain, Finland, Italy	N = 471 Drop out: 91 %	Reduce private driving and increase public transport.	Information	Subjective	Self-reported journeys and mode choices	No report	Mobile applications included a multimodal journey planner, with rewards, goal setting, and self-monitoring of CO_2 emissions.	Due to high dropout rate and insufficient reporting, no conclusions can be drawn about the impact on transport mode choice or CO_2 emissions.
Günther et al. (2020)	Germany	N = 108 Drop out: not reported	Increase energy efficient driving.	Information Social	Objective	kwh/100 km	Yes	Mobile applications used different additive nudging conditions over time in a predefined order for shared car users. Nudges included feedback and gamification.	Energy consumption was significantly reduced ($p < 0.001$). Significant reductions were in: • the gamification phases (feedback + gamification $p < 0.001$ and $p < 0.05$)

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Table 4 (*continued*)

Author and year	Country	Data	Nudge aim	Nudge type	Measures	Outcome variable	Statistically significant results	Nudge description	Results[b]
									• the financial rewards phase (feedback + gamification + financial rewards, $p < 0.05$). The feedback alone did not have a significant effect.
Van de Sompel et al. (2020)	Belgium	N = 186 • Intervention group 1. (Information + controlled motivation) n = 34 • Intervention group 2. (Information + autonomous motivation) n = 32 • Intervention group 3 (Behavioral + controlled motivation) n = 29 • Intervention group 4. (Behavioral + autonomous motivation) n = 30 • Intervention group 5. (Combination of information and behavioral + controlled) n = 31 • Intervention group 6. (Combination of information and behavioral + autonomous) n = 30	Increase children's cycling	Information Physical (sticker)	Subjective	Self-reported number of times the children commuted to school by cycling	Yes	Educational video (information nudge) and/or a sticker card (behavioral nudge), and different framings were used to nudge pupil groups.	• The results showed the main effect of the type of intervention on the average change in the number of cycling times ($F(2,182) = 15.84$, $p < 0.001$). • The change was larger in the intervention combining informational and behavioral elements ($M = 0.65$, $SE = 0.09$), compared to informational intervention alone ($M = 0.13$, $SE = 0.06$) ($SE = 0.11$, $p < 0.01$, BCa 95 % CI = [−0.72, −0.29]) or behavioral intervention alone ($M = 0.24$, $SE = 0.05$) ($SE = 0.10$, $p < 0.01$, BCa 95 % CI = [−0.61, −0.20]). • Type of motivation did not have a direct effect ($F(1,182) = 0.87$, $p = 0.35$). • An autonomous ($M = 0.38$, $SE = 0.06$) compared to a controlled motivational message ($M = 0.30$, $SE = 0.05$) did not increase the cycling times. • No interaction between the persuasive messages and the type of motivation ($F(2,180) = 0.11$, $p = 0.90$) was found.
Khoshkangini et al. (2021)	Italy	N = 410 (total of active participants) • Intervention group 1: (automatically created challenges) n = 82	Increase sustainable traveling.	Information Social	Objective	Number of trips or km traveled in a certain transport mode compared to the baseline	No report[a]	Viaggia Play&Go application promoted sustainable mobility (walking, cycling, bus or train) by creating challenges to match the preferences of the players.	• Both treatments improved mobility behavior. • Automatic challenges had statistically stronger effects compared to human designed

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Table 4 (*continued*)

Author and year	Country	Data	Nudge aim	Nudge type	Measures	Outcome variable	Statistically significant results	Nudge description	Results[b]
		• Intervention group 2. (human designed challenges) n = unclear Drop out: 48 % of the registered players						The app included gamification elements: weekly and final prizes were given.	challenges on weekly km traveled, when only improved players were considered.
Sottile et al. (2021)	Italy	N = 37 Drop out: 38 %	Decrease private driving and increase sustainable travel modes.	Information	Subjective & Objective	Travel activity data from the application and survey questionnaire: switch from private vehicle to public transport, walking or cycling, or car sharing	No report[a]	GPS based mobile application contained PTP with sustainable travel-mode alternatives (public transport, walking or cycling, car sharing) and persuasive messages. PTP's were also sent by email.	GPS data showed an 8 % shift from private cars to public transport for those use received the PTP.
Ton & Duives (2021)	Netherlands	N = 82 Drop out: 80 %	Decrease car use and increase e-bike use.	Physical	Subjective	Self-reported average share of transportation mode use before and after pilot	Yes	Provision of free e-bikes for eight weeks for car users who are willing to change their habits.	• Car use dropped from 88 % to 63 % of the days ($p < 0.01$). • E-bike use increased from 2 % to 18 % ($p < 0.01$).
Olsson et al. (2021)	Sweden	N = 380 • Intervention group 1. (financial incentive nudge) n = 96 • Intervention group 2. (moral norms nudge) n = 103 • Intervention group 3. (social norms nudge) n = 181 Drop out: 55 %	Increase cycling and motivation for behavioral change.	Information Social	Subjective	Self-reported change in mode use and motivation to change behavior	Yes	Motivational leaflets in a bike to work campaign, which included three different nudging conditions: financial motivation, moral norm, and social norm.	• Cycling increased and private driving decreased 2 weeks after the nudging interventions, but after 3 months a marginally significant effect was detected on decreased car use, but not for cycling. • There was a significant effect in decreased car use for the financial nudging condition in long term. • The change in car use and cycling was significantly influenced by progress in the motivational stage ($p < 0.01$).

[a] The study did not report a statistically significant change, but reported that nudging produced some change in either target behavior or secondary behavioral indicators.
[b] Results descriptions are reported with the amount of detail allowed by the original articles.

3.2. Uncontrolled studies

This systematic literature review also included 11 uncontrolled studies reported in nine articles (Table 4). Of the 11 studies, nine found that nudging had a positive effect. These studies may not provide as robust evidence as controlled studies, but they clarify the kind of nudges that have been used to promote sustainable traveling. Some studies performed between-subjects comparisons but did not have a control group that was not targeted by any intervention. Many studies have used within-subject designs to compare the different study phases. Six uncontrolled studies used the internet or mobile applications [26,28,33,38], two conducted information campaigns [39,40], and the other three comprised a miscellaneous group [27,31,41].

3.2.1. Information campaigns

Van de Sompel et al. [40] compared the effectiveness of informational materials (educating videos) and nudges (sticker cards) and examined the moderating role of motivational messages. Self-reported school commuting by cycling among 8–11-year-old children increased more after a combination of informational and behavioral interventions than after either intervention alone.

A more traditional leaflet-based informational campaign for employees of ten private companies resulted in increased cycling between baseline and two weeks after a 30-day campaign [39]. The researchers tested three information campaigns with either a financial incentive (possibility of winning a bike) or two different nudges: 1) moral norms (protecting the environment) and 2) social norms (let us do this together). After three months, the cycling activity of employees returned closer to the baseline, but people still drove their cars less.

3.2.2. Route-planning applications

In a study by Sottile et al. [33], longitudinal GPS data showed an 8 % shift from private car use to public transport in Rome (Italy) for university students who received PTPs using mobile applications and email. Based on self-reports, awareness of CO_2 emissions was strengthened, active mobility became more frequent, car sharing increased, and attitudes toward car use decreased; however, social norms were not affected during the 2-week intervention. PTPs included suggestions for sustainable travel alternatives, detailed environmental effects of travel choices, personalized slogans, and information on sustainable mobility. Based on these results, the authors pointed out that personalized information strategies have the potential to change behavior, despite the extremely car-centric culture of the city of Rome.

Instead, no behavioral change was observed with objective data from GPS route logs using a work-in-progress travel planner application designed to help identify and utilize low-emission travel options [26]. According to the self-report, the application was considered moderately satisfactory among participants and increased environmental awareness and self-reported behavior change toward more environmentally friendly travel routes. The application included different persuasive strategies; for example, it suggested green default options and displayed environmentally friendly options in a more prominent position on the interface.

A field experiment using a mobile application to promote sustainable urban mobility through gamification aimed to compare the effects of fully and semi-automated personalization of challenges [28]. The motivational gamification elements of the mobility application included leaderboards, badges, weekly themes, and earnings points such as the level of sustainability of the travel mode. In the game, also weekly and final prizes were assigned to top players. When analyzing only participants who completed the game, no differences were found in the effects of fully and semi-automated personalization of challenges when considering the number of trips or kilometers traveled. However, when analyzing only the data that represent positive improvements, fully automated challenges induced a statistically significant improvement in kilometers traveled.

No differences were found in travel-mode choice or attitudes toward the environment in a study that developed and tested a mobile application for multimodal journey planning, which included rewards, goal setting, self-monitoring, and reporting of disruptive events [38]. The main studies were conducted in Barcelona (Spain), Helsinki (Finland), and Milan (Italy). This was preceded by two 4-week pilot studies testing motivational messages in the application (in Trento, Italy) and automatic journey tracking, journey planners, trip history, visual feedback on CO_2 emissions, and a set of challenges that aimed to motivate users to use sustainable transportation (in Helsinki, Finland). However, the main study had a high dropout rate. Indeed, the studies suffered from discouraging elements, such as the high battery consumption of automatic journey tracking and laborious travel diaries. In addition, reactions to motivational features such as goal setting or personal CO_2 emissions, varied among the participants. Goal setting motivated some participants but was ignored by others, and information about one's own emissions did not trigger behavioral or attitude changes.

3.2.3. Other nudges

In a study by Günther et al. [27], the energy consumption of battery electric vehicles was decreased when feedback was combined with gamification, or feedback, gamification, or financial rewards together in a web application in a study by Günther et al. [27]. In addition, gamification seems to enhance knowledge of eco-driving. Feedback alone failed to affect the behavior measured using driving data from cars. During the 22-month study period, the participants habituated to eco-driving, which was evident even in the post-intervention phase, when all persuasion strategies were removed.

In a study by Ton and Duives [41], a free e-bike trial reduced car use and increased e-bike use after an 8-week pilot study among habitual car users. Additionally, commuting using regular bicycles increased after free access to e-bikes. Almost half of the participants stated that they would not have considered changing their behavior without the pilot study. However, noteworthy is that transport behavior did not change for people who used a car on all commuting days prior to the pilot. Researchers also discovered that the most important factors in reducing car use after the pilot in the following order were the purchase of an e-bike, participants' perception of e-bike safety, and the aim of using the pilot to change behavior. This study had a significant dropout rate, which may have influenced

its results.

In a study by Riener [31], a vibrotactile feedback system was administered to the car seat, one in the seating and the other in the safety belt, to inform the driver of how economically they were currently driving compared with their average at baseline tests. The driving economy was measured based on the vehicle mileage gathered in real-time from the sensors, and information was delivered to the driver with very subtle vibrations. Within-subject comparisons between the baseline and two experimental conditions showed that fuel consumption was 8 % lower with subliminal persuasion using safety-belt vibration, but not with the tactile interface in the driver's seat. Furthermore, a lower mean driving speed and speed variation were detected for sections driven under subliminal persuasion than for baseline.

4. Discussion

4.1. Overview of the findings

This systematic review shows that research on nudging toward sustainable transportation is heterogeneous regarding both interventions and their results. The studies differed significantly in terms of the content, implementation, data-gathering methods, and target groups of nudges. Furthermore, several methodological shortcomings, such as small sample sizes, short intervention durations, and high dropout rates, limit the reliability of the findings. These issues, coupled with the heterogeneity of study designs, make it difficult to draw definitive conclusions about the effectiveness of nudging in this domain. Although it is challenging to draw strong conclusions on the effectiveness of nudges in promoting sustainable transportation, some important lessons are to be learned.

Based on this review, tentative evidence shows that nudge interventions can be effective in producing changes toward more sustainable transportation behaviors. Although many of the studies included in this review failed to show or report statistically significant results, the trends often supported nudges.

As previously discussed, some open questions regarding nudges remain unresolved. According to previous studies, nudges can be effective in various domains (e.g., healthy behaviors, retirement savings, and tax compliance), but sometimes nudges do not work at all, or the same nudge type only works in some contexts [42]. As seen in the second-order meta-analysis of Bergquist et al. [10], behavioral interventions for transportation behavior are especially difficult, and different types of interventions, such as social comparison and feedback, may have very different effect sizes. This seems to be the case in the studies included. Some interventions produced effects, whereas others did not.

It is unclear when or what types of nudges produce persistent behavioral changes [43,44]. The details (e.g., context, wording, and timing) of nudging may play a larger role than the type of nudge. According to suggestions, the effectiveness of nudges is based on their scalability. Even a minor effect can be important if it affects many people, and the effect can be better observed in larger samples. Furthermore, many studies reporting statistically nonsignificant trends may have been underpowered to detect the subtle effects of nudges. In contrast, studies with positive effects had, on average, smaller samples than those that did not detect behavioral changes. These differences may also be explained by substantial differences in the aims, methods, and outcomes of the studies and not merely by sample size. Furthermore, many interventions lasted only a few weeks, which may have been insufficient to produce long-lasting behavioral changes.

One conspicuous observation was that many studies in this review suffered from significant dropout rates, which is peculiar, since theoretically, nudges aim to ease decision-making without producing significant costs for the nudgee. Nudges have been criticized for their ability to incur cognitive costs to the nudges [42]. In many of the reviewed studies, dropout was likely caused by a demanding study design that required a lot of extra work from the participants or other discouraging elements such as poor usability of the applications. The dropout rate was also high in the studies that used gamification. Although often fun and engaging, participating in a game may also be time-consuming or mentally burdensome. The high dropout rates may have led to a heavy selection bias. It is likely that the remaining participants were the most motivated and able to engage in active traveling. Furthermore, if the already active participants produced a ceiling effect in the studies, this could partly explain why many studies failed to reach statistically significant results.

We were unable to define the most efficient nudge type based on the chosen categorization of nudges [19]. Most studies have used a combination of different nudge types, typically providing information and social salience. One exception is the study of Riener [31], in which a nudge took advantage of subliminal feedback, operating outside conscious processing. Notably, subliminal nudges have not been acceptable by most of the population according to representative surveys [45].

The results showed no systematic pattern regarding the effectiveness of combinations or types of nudges. Using multiple nudges simultaneously was not consistently better than using a single nudge. However, it is possible that when considering nudges that target more specific behaviors, such as changing from cars to bicycles, we could find nudge types that work better than others in that specific situation. For example, a meta-analysis by Semenescu et al. [7] found that the psychological variables targeted by an intervention explained the largest variability in the effectiveness of interventions aimed at decreasing the car modal share. In this case, nudge interventions targeting social, cultural, and moral norms were the most effective in decreasing the car modal share.

Furthermore, some interventions included in this review were difficult to categorize in one clear category. Gamification applications typically include a wide variety of methods to influence behavior. While it can be questioned whether gamification should be considered a nudge, based on how it was utilized in the studies included in this review, it does seem to contain several nudging elements, such as social comparison. Gamification did not turn out to be superior to other nudges but appeared to work best when combined with other steering methods, such as financial rewards, providing information, and personalized feedback [27,29,30].

Studies that have managed to influence behavior have reported contradictory results for different groups. The psychological

mechanisms of ecological behavior are complex; therefore, according to expectation, one nudge does not work for all or affect everyone's behavior in an analogous way. If nudges can help overcome one obstacle created by cognitive dissonance, other barriers may still prevent behavior. For example, in one of the studies aiming to reduce private motoring, the combination of providing information and social nudges affected behavior only when traveled in the afternoon or alone, or with a family member [35]. In another study, the provision of information and social salience failed to encourage employees to increase carpooling [25]. These results suggest that travel-mode choices may be easier to make when they do not concern other people or when the behavior is perhaps less affected by schedules and time pressure, unlike when traveling to work in the morning. These results may also indicate that systemic-level changes related to the use of single-occupancy vehicles must precede changes in routine behaviors, such as commuting. Mere provision of information [25] may not produce behavior change when simultaneously the workplace supports driving, for example, by offering free parking spaces for employees.

Individual differences and life situations, such as health status, wealth, marital status, physical activity, family size, and the age of the children in the family can affect mobility. Such environmental and individual factors have rarely been considered in the reviewed studies.

In the reviewed articles, questionnaire data systematically produced more positive results than objective data, even in studies using both. This finding suggests a response bias in studies using self-reporting. The participants may have responded in the way they thought the researchers expected them to answer, or they may have adopted a socially desirable response style.

4.2. Strengths and limitations

This review was conducted through an extensive literature search of four databases. Several researchers from a multidisciplinary team independently reviewed the articles. This was done to reduce researcher bias during the data selection process. Another strength of this review was its conceptual flexibility. Research on nudges is still in its infancy and the use of nudge theory in studies is relatively limited. This systematic review provides a wide range of insights by including studies in which researchers did not explicitly label their interventions nudges. Among the articles in this review, only three [25,29,32] directly mention the nudge theory. Without a broader definition and careful assessment of the nudge concept, much of the material in this study would have gone undetected.

When selecting articles for this review, strict criteria were set for the study methodology. The behaviors of the subjects were measured before and after the intervention, and the intervention group was compared with the control group. This criterion increases the reliability of the conclusions drawn from the data, as it increases the likelihood that changes in the behavior of the intervention group are due to the intervention and not random variations. However, since so few studies met both criteria, namely before and after measurements and a control group, the working group decided to include studies without a control group. To be transparent about the reliability of the different studies, we evaluated the uncontrolled studies separately from the controlled studies.

In contrast to meta-analytic approaches (see for example Bergquist et al. [10]), which aggregate quantitative data from multiple studies to derive statistical estimates of intervention effects, our literature review synthesizes qualitative insights across a broad array of studies, highlighting the heterogeneity in intervention methods, contexts, and outcomes. While the meta-analytic method provides a robust estimate of average effects, it may obscure important nuances because of the inclusion of studies that use different definitions, measures, and intervention designs. As the interventions and behavioral outcomes in the reviewed studies are highly heterogeneous, a meta-analytic approach would risk reducing this complexity to standardized metrics that overlook important contextual differences. By contrast, our literature review approach accommodates the diversity of intervention types and the ways in which they affect different transportation behaviors. This methodology provides a more flexible framework for exploring a broader range of strategies used to promote behavioral change, which may otherwise be obscured by the comparability requirements inherent in meta-analytic methods. This qualitative perspective is crucial, especially given the challenges of directly comparing interventions that vary in scope and methodology, a limitation acknowledged in the meta-analysis by Bergquist et al. [10].

Although the review had some limitations, the strict inclusion criteria eliminated many weak studies. However, this resulted in highly heterogeneous data. The methodological shortcomings of many of the included studies weakened the reliability of this review. Not all studies were randomly sampled, and many had a high degree of attrition. As discussed above, these factors are likely to produce systematic bias. In Kristal and Whillans' [25] large-scale studies, participants were unaware of being studied. This most likely reduced not only the risk of sample bias but also the Hawthorne effect (changing behavior due to being watched) and response bias. Notably, no behavioral changes were observed in these experiments. Nevertheless, interpretation of the results is challenging because the nudge interventions were not described in detail.

The reporting also presented other gaps in the included studies. Beale and Bonsall [36] suspected that specific features or details of a nudge, for instance, the gender in the picture of an information leaflet, may affect how and to what target group the nudge has. Therefore, in some studies, the unreported features of nudges may have contributed to the results; however, the possible effects remain unknown because of scant reporting. In many articles, numerical data have been incompletely reported; for example, rarely reported effect sizes.

Finally, noteworthy is that all the studies, except one, were conducted in Europe. This raises concerns about the generalizability of the results. Cultural and legal differences between countries and regions can lead to behavioral interventions that do not have the same impact everywhere. For example, citizens from different countries differ in the types of behavior they find acceptable [45,46].

4.3. Future directions

The use of nudges to promote sustainable transportation seems to be a great challenge due to the complexity of the topic. One

essential challenge for future nudge studies is the variance in the theories used to plan behavioral interventions. The mix of different behavioral change theories makes it difficult to compare the effectiveness of nudges. For example, the following theories were used within the budget framework in the included studies:

Several studies applied the Theory of Planned Behavior (TPB) [47] to travel-mode choice interventions [29,33,36]. TPB is an influential and well-studied behavioral framework that posits that behavior is guided by favorable or unfavorable attitudes about the consequences of behavior, beliefs about the norms of important others, and perceived behavioral control of the behavior in question. As outlined in the TPB, behavior is primarily guided by the intention to act [47]. Favorable attitudes, subjective norms, and higher perceived behavioral control increase the intention and probability of performing the behavior in question.

More recent theoretical models such as the Transtheoretical Model of Change (TTM) and Stage Model of Self-Regulated Behavioral Change (SSBC) have also been utilized in some studies (e.g., Refs. [30,37]). TTM and SSBC distinguish the effects of behavioral change at distinct stages (e.g., Refs. [48–50]). The basic idea of these stage-of-change models is that the intervention is designed to influence individuals at different stages of the behavior-change process. TTM, for example, has been applied to monitor the degree of motivation for beginning, increasing, or sustaining a specific active transportation behavior [50]. A certain degree of motivation and willingness is needed to induce behavioral change, and higher stages have been shown to increase the probability of using active travel modes. The self-determination theory of motivation (SDT) of Deci and Ryan [51] used the self-determination theory of motivation as a framework for designing motivational messages for nudges [40]. Deci and Ryan [52] argue that stimulating autonomous motivation, as opposed to controlled motivation, emphasizes freedom of choice and self-direction in behavior, increases intrinsic motivation, and leads to more desirable results.

Future studies should make improvements at several research levels. Theoretical aspects related to nudging and behavioral changes should be considered more closely. Based on the nudge framework, interventions should be effortless for nudgees and expected to be the most effective when offered at the right time. The timing can be considered in at least two ways. Changing behavior is seemingly easier when it coincides with another transition in life, such as moving residences [53]. Another way of looking at timing is to identify people who are in the right stage of behavior change [48]. Interventions could steer people from one action-oriented stage to another, even though a change in behavior is not yet observable.

Methodologically, the research in this field could be improved. Preregistered controlled randomized trials are the most reliable way to investigate the effects of nudges on sustainable transportation. Sufficiently large, non-biased samples are required. Behavioral change should be measured using objective methods, not just participants' self-report. Additionally, the reporting of data and results should be more detailed and systematic. Post-surveys are needed to determine why a specific nudge did or did not work, and how the components of the nudges should be contextualized.

5. Conclusions

Our review provides evidence for the effectiveness of nudges in changing transportation behavior. In controlled studies, almost half (5/12) found that nudging influenced the behavior of at least some subgroups of participants. In the uncontrolled studies, nearly all (9/11) studies had positive effects on sustainable transportation behavior. However, given the significant methodological challenges, high variability in study designs, and mixed results, the overall evidence of the robust effects remains weak. As noted by Bergquist et al. [10], the effectiveness of behavioral interventions on transportation might be small, but not inconsequential, particularly when targeting high-impact behaviors, such as reducing car use. Even modest changes in these areas can lead to significant reductions in greenhouse gas emissions, making them crucial targets for future intervention efforts, despite the challenges. Cautious interpretation of the effectiveness of nudges in promoting sustainable transportation is needed, as well as evidence that it may be efficient when targeted and implemented correctly. Our main conclusions are as follows: No particular type of nudge was systematically more effective than others, and multiple nudges were not consistently better than one.

- The effectiveness of nudges seemed to vary according to the target groups and details of the nudges.
- This research area faces multiple methodological challenges and scarce reporting, which hinder its ability to draw strong conclusions or comparisons based on the current literature.
- Subjective data seemed to produce more positive results than objective data, which directs future research to focus on measuring objective data on actual behavioral change.

In general, the effects were subtle, and many failed to reach statistical significance or did not report them. However, even a small effect can lead to significant changes when combined with other steering methods and can be implemented on a large scale. Noteworthy is that nudges are not supposed to replace other policy methods, but supplement them. Going back to the open issues, (Hagmann et al. [54] have also demonstrated the risk of the "nudging-out" effect, meaning that introducing nudges may create the false hope that problems can be tackled without imposing considerable costs and that it might diminish support for standard policies. These issues must be considered when planning sustainable transportation nudges.

Because of the heterogeneity and methodological shortcomings of existing studies, more research is needed before stronger conclusions can be drawn or applicable meta-analyses can be conducted. Studies with more precise reporting, longer follow-up periods, and larger samples with control groups are needed to gain a better understanding of how nudges can be used in different behavioral change contexts.

CRediT authorship contribution statement

Marianna Melin: Writing – original draft, Data curation, Writing – review & editing, Visualization, Conceptualization, Formal analysis, Methodology, Investigation, Project administration. **Anna Makkonen:** Writing – original draft, Conceptualization, Writing – review & editing, Data curation, Formal analysis. **Siiri Yrjölä:** Writing – review & editing, Conceptualization, Writing – original draft, Formal analysis. **Juha Peltomaa:** Writing – review & editing, Data curation, Conceptualization, Writing – original draft. **Nils Sandman:** Writing – review & editing, Data curation, Writing – original draft, Conceptualization. **Jarno Tuominen:** Writing – original draft, Data curation, Writing – review & editing, Visualization, Conceptualization. **Kaisa Vuori:** Writing – original draft, Writing – review & editing, Investigation, Conceptualization. **Marko Tainio:** Supervision, Conceptualization, Writing – review & editing, Data curation, Writing – original draft. **Paula Salo:** Data curation, Methodology, Supervision, Writing – review & editing, Formal analysis, Project administration, Visualization, Conceptualization, Funding acquisition, Resources, Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Anna Makkonen, Juha Peltomaa, Nils Sandman, Jarno Tuominen, Kaisa Vuori, Marko Tainio, Paula Salo reports financial support was provided by Strategic Research Council. Marianna Melin reports financial support was provided by Finnish Cultural Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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