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Bicycle helmets and risky behaviour: A systematic review

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ABSTRACT

A long-standing argument against bicycle helmet use is the risk compensation hypothesis, i.e., increased feelings of safety caused by wearing a helmet results in cyclists exhibiting more risky behaviour. However, past studies have found helmet wearing is not associated with risky behaviour, e.g., committing a traffic violation was positively associated with a lower frequency of helmet use. There is a lack of consensus in the research literature regarding bicycle helmet use and the risk compensation hypothesis, although this gap in knowledge was identified in the early 2000s. This is the first study to carry out a systematic review of the literature to assess whether helmet wearing is associated with risky behaviour. Two study authors systematically searched the peer-reviewed literature using five research databases (EMBASE, MEDLINE, COMPENDEX, SCOPUS, and WEB OF SCIENCE) and identified 141 unique articles and four articles from other sources. Twenty-three articles met inclusion criteria and their findings were summarised. Eighteen studies found no supportive evidence helmet use was positively associated with risky behaviour, while three studies provided mixed findings, i.e., results for and against the hypothesis. For many of these studies, bicycle helmet wearing was associated with safer cycling behaviour. Only two studies conducted from the same research lab provided evidence to support the risk compensation hypothesis. In sum, this systematic review found little to no support for the hypothesis bicycle helmet use is associated with engaging in risky behaviour.
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1. Introduction

The risk compensation hypothesis for bicycle helmet use posits that wearing a helmet leads to riskier behaviour thereby offsetting any safety benefit afforded by the helmet (Adams and Hillman, 2001a). This argument has been used to oppose the introduction of bicycle helmet legislation in jurisdictions with no such legislation or to repeal bicycle helmet legislation in jurisdictions where such legislation currently exists (Rehfisch, 2017; Sustainable Transport Coalition of Western Australia, 2015). Some cycling advocates have extended the risk compensation hypothesis to conclude bicycle helmet use should not be promoted or legislated (Cyclists' Rights Action Group, 2013). To examine the risk compensation hypothesis, previous research has mostly focused on how helmet wearing affects cycling speed (Fyhri, Bjørnskau & Backer-Grøndahl, 2012; Phillips, Fyhri, & Sagberg, 2011; Messiah, Constant, Contrand, Felonneau, & Lagarde, 2012; Fyhri, Sundfør, Weber, &

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Phillips, 2018). However, the effect of helmet wearing on actual risk-taking or illegal behaviour has been mostly overlooked in the literature.

There are important aspects that can be deduced from the definition of the risk compensation hypothesis with regards to bicycle helmets. If risk compensation is assumed to be true, the effect is a measurable change in behaviour in a specific direction. If a person changes their usual helmet wearing behaviour, i.e., start or stop wearing a helmet, their level of risk taking would either increase, decrease or stay the same. Risk compensation, as it is typically defined and understood, is only one of six possible scenarios, namely a usual non-helmet wearer puts on a helmet and increases their risk taking. Importantly, evidence in the opposite direction, i.e., taking a helmet off leads to less risky behaviour, is not evidence in support of risk compensation as it is a type of logical fallacy (i.e., affirming the consequent). Note a more inclusive definition is risk homeostasis which could be taken as a change in risky behaviour, increase or decrease, following a change in helmet wearing behaviour.

Change in behaviour after a cyclist starts to wear a helmet and the direction of the effect is not always presented in the literature. Some studies have tested and shown that cyclists who usually wear a helmet ride at a slower speed when cycling without a helmet (Phillips et al., 2011). Although this finding suggests not wearing a helmet leads to less risky behaviour (lower speed), it does not provide any evidence for the opposite direction to support risk compensation (i.e., whether wearing a helmet leads to cycling at a higher speed). Nevertheless, such findings are sometimes considered as support for the risk compensation hypothesis in the research literature (Phillips et al., 2011).

Other studies in the risk compensation literature do not measure changes in behaviour. For example, cross-sectional studies do not include repeated measurements and, therefore, no baseline data is collected to estimate changes in risk-taking or illegal behaviour after wearing a helmet.

In another study, the association between wearing a bicycle helmet and the behaviour of motor vehicle drivers was tested. As part of a study to measure motor vehicle overtaking distances for various lane positions for cyclists, Walker (2007) concluded that motorists overtake at significantly closer distances when the cyclist is wearing a helmet than not. A re-analysis of this study found the statistical significance from the original study was due to an overpowered study design for detecting a small effect size and the effect vanished when passing distance was categorised by the one-metre rule (Olivier and Walter, 2013).

Case-control studies have shed some light on helmet use and cycling behaviour. For example, Bambach, Mitchell, Grzebieta, and Olivier (2013), in an analysis of linked New South Wales (NSW) police and hospital data of cyclists in a motor vehicle collision, found helmet users were less likely to drink alcohol and cycle or to disobey traffic controls. However, helmet users were more likely to cycle in areas with higher posted speeds for motorised traffic and less likely to cycle in a bike lane. Illegal cycling behaviour among non-helmet users was also noted in a Spanish study (Lardelli-Claret et al., 2003) while a New York study found helmet use was negatively associated with alcohol use (Sethi et al., 2016). Additionally, an earlier NSW study found proportions of cyclists slightly but consistently increased compliance with road rules from before to after bicycle helmet legislation when helmet use increased from 25% to 77% for cyclists 16 years or older (Walker, 1991).

There is a lack of consensus in the research literature regarding bicycle helmets and the risk compensation hypothesis, and this gap in knowledge was identified at least 17 years ago (Thompson, Thompson, & Rivara, 2001). Therefore, this study aims, for the first time, to shed light on the potential association between bicycle helmet use and risk compensation by systematically reviewing the literature on bicycle helmet wearing and risky behaviour. The authors are not aware of any previous systematic reviews focussing on this question.

2. Methods

To address the research question, a systematic review of the peer-reviewed literature was performed on 17 May 2017. In accordance with the study protocol (unpublished protocol available from corresponding author), the peer-reviewed literature was searched for studies with bicycle helmet content from five research databases (EMBASE, MEDLINE, COMPENDEX, SCOPUS, and WEB OF SCIENCE). The search terms were (bicycl* OR cycl*) AND (helmet*) AND (risk*). In relation to EMBASE, the subject headings for ‘‘bicycle”, ‘‘helmet”, and ‘‘high risk behavior” were used. In relation to MEDLINE, the subject headings for ‘‘bicycling”, ‘‘head protective devices”, and ‘‘risk taking” were used.

The search and removal of duplicate documents were performed independently by two researchers (JO & ME). A title and abstract screen assessment of the articles was performed by the same researchers. Study authors were contacted if relevant data was not reported, but the study met current systematic review inclusion criteria. Study authors were also contacted for a full-text report, when published abstracts met other inclusion criteria. Google Scholar alerts were used to identify relevant articles published after the original search date. The remaining articles were read in full and assessed against inclusion criteria and data was extracted with adherence to the PRISMA statement (Moher, Liberati, Tetzlaff, Altman, & Group, 2009). The included studies were independently summarised by two authors (ME & IR) in relation to their sample, study design, method of data collection, whether risky behaviour was observed or reported in a cycling environment, whether data collection was longitudinal to allow the measurement of change in behaviour, and interpretation of results. Conflicts were first discussed by the two reviewers and unresolved disputes were adjudicated by a third author (JO).

In accordance with the protocol, reviewers categorised all articles into four types including commentaries, systematic reviews of previous studies, computer simulations and lab studies, and epidemiological studies (e.g., case-control studies

of cycling crash data). To be included in the current systematic review, articles had to provide first instance data. Studies reporting the association between bicycle helmet use and risky behaviour such as disobeying traffic laws were also included.

Commentaries, response letters, and reviews of the literature were included for a full-text review; however, any relevant data were extracted from the source material. Systematic reviews of previous studies were also included for a full-text review to identify relevant source data; however, these reviews were not included in the current systematic review. Relevant computer simulations, lab studies, and epidemiological studies were included for a full-text summary.

In this systematic review, an ideal study would report cycling data extracted from the real world using a randomised sample (i.e., cyclists randomised to either wear or not wear a helmet) including details of any crashes. On the other end of the spectrum, the poorest studies are commentaries, studies that lack a control group, studies that use convenience sampling, and studies that report proxy measures for risk taking.

It is unlikely the results of the included studies can be combined numerically, such as in a *meta*-analysis, as there are no single measures of risky behaviour. For example, some studies may report proportions of cyclists who disobey traffic rules while other studies may consider cycling speed as a measure of risky behaviour. Therefore, the included studies were synthesised qualitatively with a descriptive analysis of common themes across all studies.

3. Results

The flow diagram for reviewed studies is given in Fig. 1. A search of the peer-reviewed literature resulted in 190 articles, out of which 49 were duplicates and were removed from the list. Four other articles from other sources were added into the list resulting in 145 records. This includes a recently published peer review article (Fyhri et al., 2018) that was initially

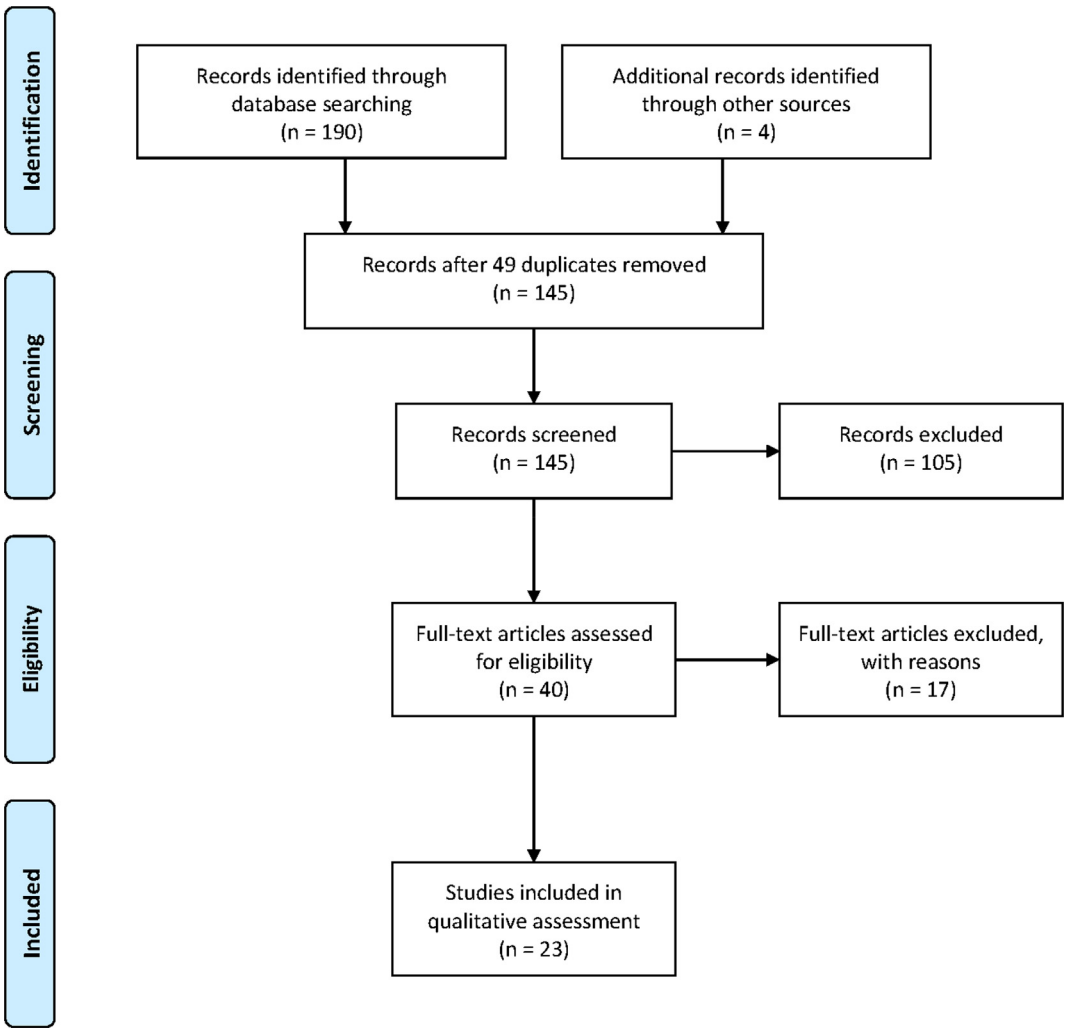


Fig. 1. PRISMA Flowchart for the systematic review of the association between bicycle helmet wearing and risk compensation.

identified from an abstract found in the 2015 International Cycling Safety Conference proceedings (Sundfør, Fyhri, Phillips, & Weber, 2015). After screening the titles and abstracts, 105 articles were excluded from the study and 40 articles were included for a full-length assessment. Finally, 17 additional studies were excluded leaving 23 eligible studies. A technical report was identified from other sources (Walker, 1991); however, it was not included for further consideration since it was not peer-reviewed.

Among the 17 excluded articles, ten studies were commentaries, reviews of the literature or response letters (Adams and Hillman, 2001a, 2001b, 2001c; Thompson et al., 2001a, 2001b; Chapman and Curran, 2004; Newbold, 2012; de Jong, 2012; Hagel, Yanchar, Society, & Committee, 2013; Melo, Berg & Inaba, 2014), four studies did not provide any relevant information for the purpose of the current systematic review (Barczyk et al., 2013; Boufous, de Rome, Senserrick, & Ivers, 2012; McCarthy, 1991; Sieg, 2016), two studies did not provide first instance data (de Jong, 2012; Olivier and Terlich, 2016), and one study was not peer-reviewed (Walker, 1991).

The 23 included studies are summarised in Table 1 and detailed summaries are provided in the appendix. The table is organised by method of data collection which can be viewed as a proxy for study quality starting with the lowest ranking method: self-reported surveys (n = 8 studies), crash data (n = 8 studies), and experimental data (n = 7 studies). The included studies were published between 1994 and 2018, five studies each were conducted in the United States (Gielen et al., 1994; Klein, Thompson, Scheidt, Overpeck & Gross, 2005; Crocker, King, Cooper, & Milling, 2012; Webman et al., 2013; Salon and McIntyre, 2018) and Norway (Fyhri et al., 2012; Phillips et al., 2011; Fyhri et al., 2018; Fyhri and Phillips, 2013; Lajunen, 2016), followed by four studies in Spain (Lardelli-Claret et al., 2003; Meneses Falcón, García, & Avilés, 2010; Martínez-Ruiz et al., 2014), three studies in Australia (Bambach et al., 2013; Buckley, Sheehan & Chapman, 2009; Washington, Haworth & Schramm, 2012), two studies each in the United Kingdom (Walker, 2007; Gamble and Walker, 2016) and in Germany (Orsi, Ferraro, Montomoli, Otte & Morandi, 2014; Schleinitz & Petzoldt, 2017), one study in France (Messiah et al., 2012), and finally one study compared cycling behaviour in Brisbane, Australia and Copenhagen, Denmark (Chataway, Kaplan, Nielsen, & Prato, 2014).

Most of the included studies collected data in a cycling environment, although four studies did not. They include reporting drug/alcohol and school related risky behaviours (e.g., alcohol/tobacco use, skipping school and bullying) (Klein et al., 2005), engaging in risky behaviour for other transport modes (Buckley et al., 2009), behaviours related to riding a motorcycle (e.g., riding motorcycle when consumed alcohol) and driving a motor vehicle (e.g., using seatbelt), but not riding a bicycle (Meneses Falcón et al., 2010), and an experimental study where risky behaviour was measured by inflating a balloon on a computer screen (Gamble and Walker, 2016). Only three studies measured cycling behaviour when the cyclist was not wearing a helmet then later when the cyclist was wearing a helmet (Phillips et al., 2011; Fyhri et al., 2018; Fyhri and Phillips, 2013).

In total, two studies support the risk compensation hypothesis, three studies reported mixed results, and eighteen studies were unsupportive. Importantly, the studies of the highest quality (change in behaviour measured from experimental data collected in a cycling environment) were all unsupportive of the risk compensation hypothesis. Additionally, there were ten studies that suggest helmeted cyclists exhibit safer cycling behaviour than cyclists who do not wear helmets (Meneses Falcón et al., 2010; Martínez-Ruiz et al., 2014; Orsi et al., 2014; Klein et al., 2005; Crocker et al., 2012; Webman et al., 2013; Salon and McIntyre, 2018; Buckley et al., 2009; Fyhri et al., 2012; Washington et al., 2012).

4. Discussion

The peer-reviewed literature reporting bicycle helmet use and risky behaviour was, for the first time, systematically searched to assess the risk compensation hypothesis with respect to helmet wearing. Twenty-three studies were included with eighteen not supportive, three reporting mixed results, and two studies supportive of the risk compensation hypothesis. The two supportive studies were both conducted in the United Kingdom by the same lab (Walker, 2007; Gamble and Walker, 2016). Note that another group of authors have published multiple papers on this topic and none of their studies support the risk compensation hypothesis for helmets (Fyhri et al., 2018; Sundfør, Fyhri, Phillips, & Weber, 2015; Fyhri et al., 2012; Phillips et al., 2011; Fyhri and Phillips, 2013). Overall, the current systematic review has found little to no support that bicycle helmet use is associated with engaging in risky behaviour.

Our search identified one non-peer reviewed report which was not included in our summary of articles (Walker, 1991). In this study, adult cyclists in NSW were observed before and after bicycle helmet legislation. The proportions of cyclists complying with traffic rules slightly increased between the two surveys while helmet wearing had a 52% increase (25% in 1990 to 77% in 1991) for cyclists 16 years or older. That is, increased helmet wearing was not associated with an increase in illegal cycling behaviour.

The included studies assessed the association of helmet use and various forms of risky behaviour. Most studies, however, did not directly measure risk compensation through testing whether feeling safer while wearing a helmet leads to actual riskier behaviour (i.e., changes in behaviour). Rather, these studies tested the risk compensation hypothesis by testing the association between helmet wearing and perceived risk of bicycle injury, but not on actual risk-taking behaviour (Gielen et al., 1994; Lajunen, 2016); by testing the relationship between helmet use and general risk-taking behaviour, not specifically cycling related risky behaviour (Klein et al., 2005); by using a cross-sectional design that did not examine changes in behaviour without and then with a helmet (Fyhri et al., 2012; Messiah et al., 2012; Klein et al., 2005; Salon and McIntyre,

Table 1
Summary of studies meeting selection criteria.

Author	Country	Data Collection	Cycling Environment	Change in Behaviour	Risk Measure	Summary	Supports Hypothesis[a]
Gielen et al. (1994)	United States	Self-report survey	Y	N	Risk perception	Perceived risk of a bicycle injury was not associated with helmet use in Howard County (helmet law, <16 years) and was negatively associated with helmet use in Baltimore (no law, no promotion campaign) and Montgomery counties (helmet promotion campaign)	✗✓
Klein et al. (2005)	United States	Self-report survey	N	N	Risk taking scale	31.5% increase on the risk-taking scale (alcohol/tobacco use, skipping school, and bullying) for non-helmet users	✗
Buckley et al. (2009)	Australia	Self-report survey	N	N	Other transport modes	Failing to wear a helmet was significantly associated with engaging in other transport-related risks	✗
Meneses Falcón et al. (2010)	Spain	Self-report survey	N	N	Other transport modes	Helmet wearing was negatively associated with risky behaviour and positively associated to safe behaviour	✗
Fyhri et al. (2012)	Norway	Self-report survey	Y	N	Traffic violations	Traffic violations were negatively associated with helmet use	✗
Washington et al. (2012)	Australia	Self-report survey	Y	N	Crash injury, Risk perception	Wearing a helmet is associated with a reduction in crash injury risk and an increase in perceived risk of cycling	✗
Chataway et al. (2014)	Australia & Denmark	Self-report survey	Y	N	Risk perception	Helmet wearing is positively and negatively associated with fear of traffic and distracted cycling, respectively.	✗
Lajunen (2016)	Norway	Self-report survey	Y	N	Risk perception	Risk of getting seriously injured was not associated with helmet use	✗
Lardelli-Claret et al. (2003)	Spain	Crash data	Y	N	Traffic violations	Cycling at excessive or dangerous speed was not significantly associated with helmet use	✗
Crocker et al. (2012)	United States	Crash data	Y	N	Alcohol use	Alcohol use was negatively associated with helmet use	✗
Bambach et al. (2013)	Australia	Crash data	Y	N	Traffic violations, alcohol use, High posted speed	Helmet use was positively associated with cycling in risky areas and negatively associated with disobeying a traffic control and alcohol use	✗✓
Martínez-Ruiz et al. (2013)	Spain	Crash data	Y	N	Traffic violations	Helmet wearing was not associated with traffic infractions or collision with another vehicle	✗
Webman et al. (2013)	United States	Crash data	Y	N	Cycling direction, Bike lane, alcohol use	Helmet wearing was associated with riding with the flow of traffic and riding within bike lanes when available; Helmet use was associated with a non-significant decrease in the odds of alcohol use by 47%	✗
Martínez-Ruiz et al. (2014)	Spain	Crash data	Y	N	Crash risk, Crash fault	Proportion of young cyclists using helmets was higher in the general population than in those who were responsible for crashes	✗
Orsi et al. (2014)	Germany	Crash data	Y	N	Alcohol use	Cyclists who did not wear a helmet were more than twice as likely to be intoxicated as those who did	✗
Salon and McIntyre (2018)	United States	Crash data	Y	N	Crash fault	Helmet wearers had a 52% reduction in the odds of being at fault in a crash versus non-wearers; There was no association between helmet wearing and riding on streets without a bicycle lane/path	✗
Walker (2007)	United Kingdom	Experiment (Naturalistic)	Y	N	Vehicle passing distance	Motor vehicle drivers who overtook the author gave less space on average when he wore a helmet	✓
Phillips et al. (2011)	Norway	Experiment (Field)	Y	Y	Cycling speed	Participants who used own helmet cycled more slowly when cycling without a helmet; No differences among those who were not "accustomed to helmets"	✗

(*continued on next page*)

Table 1 (*continued*)

Author	Country	Data Collection	Cycling Environment	Change in Behaviour	Risk Measure	Summary	Supports Hypothesis[a]
Messiah et al. (2012)	France	Experiment (Field)	Y	N	Cycling speed	Speed was higher among helmeted than among non-helmeted male cyclists in low average speed areas, but not in higher average speed areas or among females; It is unclear if the direction of the effect supports risk compensation	✗✓
Fyhri and Phillips (2013)	Norway	Experiment (Field)	Y	Y	Cycling speed, Heart rate	Regular helmet users ride slower without a helmet and faster with a helmet; No association for non-users	✗
Gamble and Walker (2016)	United Kingdom	Experiment (Laboratory)	N	N	Balloon analogue risk task	Wearing a helmet was associated with higher risk-taking scores and higher sensation seeking than when wearing a baseball cap	✓
Schleinitz et al. (2017)	Germany	Experiment (Naturalistic)	Y	N	Cycling speed	Helmet wearing was not associated with cycling speed after adjusting for trip length	✗
Fyhri et al. (2018)	Norway	Experiment (Field)	Y	Y	Cycling speed	Helmet removal was not associated with a decrease in non-routine helmet user speed, even after a habituation period	✗

Key: ✓ (supportive evidence), ✗ (not supportive evidence), ✗✓ (mixed evidence), **Y** (yes), **N** (no).
[a] Hypothesis tested: Bicycle helmet use is associated with risky behaviour.

2018; Washington et al., 2012; Orsi et al., 2014; Chataway et al., 2014; Lajunen, 2016; Meneses Falcón et al., 2010; Martínez-Ruiz et al., 2014; Martínez-Ruiz et al., 2013); or by collecting data on the association between helmet use and risky behaviour in a potentially irrelevant context (Gamble and Walker, 2016).

Additionally, the concept of risk compensation was tested in opposite and sometimes illogical directions for the purposes of this review, i.e., whether not wearing a helmet leads to less risky behaviour (Phillips et al., 2011; Fyhri and Phillips, 2013) or whether alcohol leads to wearing a helmet or vice-versa (Orsi et al., 2014).

Finally, barriers for helmet use have not been tested in most studies. Specifically, it is unclear whether wearing or not wearing a helmet is due to the level of feeling safe or if there are other factors involved. As stated by Lajunen (2016), barriers for helmet wearing are more related to lack of comfort such as being too cold or too hot, or not fitting a hairstyle. However, subjective risk of getting into a crash and suffering serious injuries were not factors for wearing a helmet. Therefore, to increase helmet wearing, improvement in helmet design should be taken into consideration.

There are important implications of this review on bicycle helmet effectiveness. Case-control studies of crash data can accurately estimate helmet effectiveness if helmet use and having a crash are independent events (Olivier, 2017). However, if helmeted cyclists are more risk averse than unhelmeted cyclists, then case-control studies of crash data underestimate bicycle helmet effectiveness. Ten included studies found helmet use was associated with safer behaviour than unhelmeted cyclists, while only two studies found helmet use was associated with riskier behaviour. If it can reasonably be assumed risky behaviour increases the likelihood of a bicycle crash, then bicycle helmets are likely more effective than previously believed (Olivier and Creighton, 2017; Olivier and Radun, 2017).

The results from this systematic review should not be taken as supportive of bicycle helmet promotion or legislation in isolation. Instead, strategies to increase helmet use should be viewed as complementary to other safety efforts. Segregated cycling infrastructure can help mitigate collisions between unpowered wheeled vehicles and motorised vehicles, which often result in serious injury for the vulnerable road user. Purpose-built cycling infrastructure has the additional benefit of making cycling more attractive to the casual cyclist. Legislation that is supportive of cycling, in jurisdictions where this does not already exist, should be explored. Additionally, current helmet technology could be improved.

There are several limitations to this systematic review. First, risk compensation has not been directly measured in the literature which may provide inaccurate results. Additionally, even when proxy measures were used such as cycling speed, only three studies observed changes in behaviour from not wearing to wearing a helmet. Proxy measures such as speed may also be problematic as this measure may be informative for many cycling styles but not necessarily indicative of risky behaviour for sport cyclists. Second, most articles identified in this search were commentaries regarding other studies without providing any data on the association between bicycle helmet wearing and risky behaviour. Only 23 studies were identified that provided first instance data. Third, the causal relationship between helmet use and risky behaviour is difficult to establish since randomising participants to wear or not wear a helmet is often considered unethical. A recent study did, however, collect data on cycling speed in a random crossover design which did not support the risk compensation hypothesis (Fyhri et al., 2018). Although this systematic review was not supportive of the risk compensation hypothesis for bicycle helmets, risk compensation as a general phenomenon cannot be ruled out.

5. Conclusions

Supporters of risk compensation argue against bicycle helmet wearing as they hypothesise the protective benefit is offset by risky behaviour. This systematic review of the peer-reviewed literature found little to no supportive evidence of the risk compensation hypothesis and bicycle helmet wearing. Although two out of the 23 studies were supportive of risk compensation, ten other studies found helmet wearing was associated with safer cycling behaviour.

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Conflicts of interest

The authors declare that there are no conflicts of interest.

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Appendix

The twenty-three studies included for a qualitative assessment are summarised below in chronological order of publication. The limitations of each study are also discussed.

Gielen et al. (1994)

A self-report survey was conducted on 3276 school children in three American counties that differed in the strategies they used to promote helmet wearing. Howard County had a bicycle helmet law (<16 years), Montgomery County had an ongoing bicycle helmet promotion campaign only, and Baltimore County had neither helmet legislation nor an ongoing promotional campaign. A multivariable analysis (adjusted for grade, sex, ethnicity, and frequency of bicycle riding) showed that risk-taking was not related to helmet use. It also showed that perceived risk of injury was not associated with helmet wearing in Howard County; however, it was negatively associated with helmet wearing in Baltimore and Montgomery counties. The results from this study were mixed regarding risk compensation when it comes to the issue of perceived risk of injury and helmet use. Caution should be exercised when interpreting the results from this study as risk-taking was operationalized as individual's predisposition towards risk taking in general, not specifically in relation to cycling. Therefore, the findings of this study might not be generalisable to the cycling population.

Lardelli-Claret et al. (2003)

Data was collected from a cross-section of 22,814 Spanish cyclists involved in an injurious crash from 1990 to 1999 recorded in the Spanish Register of Traffic Crashes with Victims. This study aimed to examine the relationship between committing a traffic violation in a crash and voluntary use of a bicycle helmet. The study period pre-dates a bicycle helmet law introduced in 2000 for travel between cities. The authors found that committing a traffic violation was positively associated with a lower frequency of helmet use (adjusted odds ratio (aOR) = 0.63, 95% confidence interval (CI): 0.58–0.69). Cycling at excessive or dangerous speed, however, was not significantly associated with helmet use either alone (aOR = 0.95, 95% CI: 0.56–1.61) or in combination with any other violation (aOR = 0.97, 95% CI: 0.79–1.20). The use of crash data may be subject to selection bias, as committing an infraction is related to the risk of being involved in a crash. Therefore, the proportion of infractions among the group of cyclists involved in traffic crashes should be higher than for the whole population of cyclists.

Klein et al. (2005)

Data was collected on a cross-section of 112,843 multinational school children (11, 13 and 15 years) in the 1997/98 academic year as part of the Human Behavior in School Children (HBSC) study. Students were identified from a cluster sample of n = 26 schools. The self-reported survey was used to identify factors that predict bicycle helmet use. The authors found a 31.5% increase on a risk-taking scale (i.e., alcohol and tobacco use, skipping school, and bullying) for cyclists who do not wear helmets. There are important limitations of this study with regards to risk compensation. Risk-taking, operationalized in this study as the risk-taking scale, is a measure of general risk-taking behaviour and not necessarily those relevant to bike riding. Although some jurisdictions in the USA and Canada have bicycle helmet laws, this was not addressed in the analysis. Therefore, this study does not directly address risk compensation and helmet use and the results may not be generalisable to the cycling population.

Walker (2007)

In a naturalistic experimental study, a researcher aimed to examine the association between proximity of overtaking and other factors including helmet wearing. In this study, the author was the experimenter riding a bicycle with or without a helmet, while the participants were drivers who overtook him. The author stated that bicycle distance from the road edge was controlled in the analysis. The author found that motor vehicle drivers who overtake cyclists give less space to cyclists who are wearing a helmet, which supports the risk compensation hypothesis.

This study is limited due to potential experimenter effects as the author was the sole bicyclist and the cycling route chosen covered two English cities that were part of the author's route to work. A re-analysis of the data from this study found overtaking distance was similar for close overtaking and differences emerged for distances over 2 m (Olivier and Walter, 2013). Finally, in this study, wearing a helmet and its effect on a cyclist engaging in risky behaviour were not tested. A critical review of this study can be found elsewhere (Radun and Lajunen, 2018).

Buckley et al. (2009)

In an interventional experiment, the authors aimed to examine the effectiveness of a theory-based injury prevention program (Skills for Preventing Injury in Youth, SPIY) on bicycle helmet wearing for 506 year nine students (age 13–14 years) from 6 schools in low socioeconomic areas of southwest Queensland, Australia. In this study, two schools were considered as the experimental group (N = 268) and 4 other schools served as the comparison group (N = 238). The authors found that the intervention was associated with a 20% decrease in self-reported cycling without a helmet in the intervention group; while no change was observed in the comparison group after 6 months. This study also showed that helmet wearing is negatively associated with engaging in other transport-related risks. This study is limited for the purposes of this systematic review as it did not test whether helmet wearing is related to bicycle-related risky behaviour.

Meneses Falcón et al. (2010)

In the Madrid and Andalusian regions of Spain, 3612 secondary students were randomly selected from participating schools. The researchers collected data on risky behaviours related to road safety including bicycle helmet use. The lead author provided cross-tabulations of bicycle helmet wearing and other risky behaviours which were not reported in the article.

In their data set, bicycle helmet wearing was more common among those who wear motorcycle helmets (most of the time: 40.0% vs never: 22.6%), who use a seatbelt while in the car with their parents (35.6% vs 6.8%), and who use a seatbelt while in the car with a friend (38.2% vs 12.1%). Helmet wearing was lower among those who have ridden a motorcycle when the driver consumed alcohol (24.4% vs 35.4%), who have driven a motorcycle having consumed alcohol (23.2% vs 34.0%), who crossed the street when they could not (26.6% vs 49.4%), and who like taking risks (24.3% vs 46.4%). Overall, helmet wearing is more common for those reporting safe behaviours and less common for those reporting risky behaviours. However, these results are limited for this review as the self-reported risky behaviours were not related to cycling.

Phillips et al. (2011)

In Oslo, a field experimental study recruited 35 cyclists irrespective of whether they usually wear or do not wear a helmet. They then rode a bike for 0.4 km downhill with or without a helmet. In another analysis, participants were dichotomised according to their usual frequency of helmet usage in everyday life. An additional "follow-up" experiment was carried out with 13 participants who rode a bicycle with two hands on the handlebars ("safe condition") and with one hand on the handlebars ("unsafe condition").

The authors found that participants who used their own helmet in the experiment cycled more slowly when cycling without a helmet. They also reported increased personal insecurity and perceived risk of having an accident when cycling without a helmet. However, no difference was shown among those who do not usually wear a helmet. In the follow-up experiment, cyclists reported higher levels of personal insecurity and accident risk, and cycling more slowly when riding in the less safe condition (i.e., with one hand on the handlebars). A limitation of this study is potential observer/experimenter bias due to lack of blinding. Note the authors conclude their study supports the risk compensation hypothesis, although the effect is in the wrong direction (i.e., not wearing a helmet leads to less risky behaviour).

Crocker et al. (2012)

The authors assessed the association between alcohol use and helmet wearing in a prospective study of 427 injured cyclists who presented to a regional trauma centre in the United States between December 2006 and April 2009. Data were collected on helmet use, type of helmet, self-reported skill level, alcohol used before or during a ride, date and time of the day, severity of head/brain injury, and context of the crash. The authors found that drinking alcohol is positively associated with unsafe cycling practices and risk of injury, and alcohol use is negatively correlated with helmet use.

Fyhri et al. (2012)

Data was collected on a cross-section of 1504 randomly recruited bicycle owners in an insurance register in September 2008. The authors found that traffic violations were negatively related to helmet use and safety equipment use. In addition, being a fast cyclist and perceived risk were positively related to helmet use. The authors concluded that the perceived lack of the effectiveness of bicycle helmet legislation was more likely to be due to a population shift, as opposed to risk compensation mechanisms.

Messiah et al. (2012)

This study examined 1798 cyclists (85% were non-helmet users) who borrowed a bicycle for their own use in a promotional helmet campaign in Bordeaux, France. The authors found the observed speed was higher among helmeted male cyclists (19.2 km/h) than among non-helmeted male cyclists (16.8 km/h, $p < 0.001$); however, the difference was observable

for areas of low average speed only and no change was found among females. The authors conclude that if risk compensation exists, then its effects are small.

The data used in this study originated from a naturalistic randomised control trial from the same authors (Constant et al., 2012). However, the randomised groups were not relevant for this secondary analysis. In the original study, one group received only a brochure promoting helmet use, the other only a free helmet, the third group received both the brochure and helmet, while the forth did not receive anything and served as a control group. For the purpose of assessing the risk compensation hypothesis, this study is a prospective cohort study of cyclists who do not usually wear helmets with some of them choosing to wear helmets. Repeated observations for the same cyclist were accounted for using generalised estimating equations; however, all cyclists were not observed both wearing and not wearing a helmet and the change in cycling speed is not necessarily in the proper order (i.e., change in speed without and then with a helmet). Therefore, it is unclear whether this study is relevant for risk compensation and bicycle helmets. A critical review of this study can be found elsewhere (Radun et al., 2018).

Washington et al. (2012)

A cross-section of 2500 Queensland children over 17 years old were recruited via advertising, media coverage, posting on cycling forums, distribution of promotional flyers and word of mouth. This study aimed to examine the association between bicycle-related injuries and perceived risk of cycling. The authors found that participants who reported always wearing a helmet were associated with a reduction in crash injury risk and an increase in perceived risk of cycling. A limitation of this study is the non-random selection of participants. Therefore, the results may not be representative of the cycling population.

Bambach et al. (2013)

A retrospective case-control study of 6745 cyclists injured in a motor vehicle collision were identified from linked NSW police and hospital crash data from 2001 to 2009. This study examined the effect of bicycle helmet use on head injury as well as the association between helmet wearing and bike-related risky behaviours. The authors found that cyclists who did not wear a helmet were more likely to engage in risky behaviour such as disobeying a traffic control and cycling with a blood alcohol concentration greater than 0.05; however, they were less likely to cycle in risky areas such as roads with high speed motorised travel. The primary limitation of this study is a potential selection bias from case-control designs. A follow-up study found similar results using propensity score stratification to lessen the influence of potential allocation bias on synthetic data generated from the published summary statistics (Olivier and Terlich, 2016).

Fyhri and Phillips (2013)

A field experimental study on 27 participants was conducted in Oslo, Norway. Participants were categorised as being a regular helmet wearer (yes or no) and heart-rate variability was used as a measure of psychophysiological load. The participants cycled with one hand in order to increase differences between measures. Each participant was asked to wear their own helmet either in the first or second round of cycling. If they did not arrive with a helmet, they were loaned one. The authors found that cyclists who use a helmet more frequently were more likely to ride faster when wearing a helmet and more likely to ride slower when not wearing a helmet. They also found that participants who normally wear a helmet were more likely to have a higher psychological load when not wearing a helmet, compared to those who are not accustomed to helmet wearing. However, there was no change for participants who do not normally use a helmet. No significant correlation was found between pace and heart rate.

The authors concluded their findings support the risk compensation hypothesis theory; however, the observed effect was in the wrong direction (i.e., regular helmet users rode slower without a helmet). It is not clear whether participants were randomised to treatment (i.e., helmet use), nor whether all participants rode on both sites (cycle path or cycle lane).

Martínez-Ruiz et al. (2013)

A quasi-induced exposure approach using cross-sectional crash data was used to identify factors related to the risk of causing a road crash that involve cyclists in Spain. The sample was taken from the Spanish Register of Traffic Crashes with Victims and consisted of cyclists who were involved in single (n = 3827) or one-cyclist-one-motor vehicle (n = 19007) injury crashes between 1993 and 2009. Only crashes in which one party committed an infraction were included in a logistic regression analysis to predict crash responsibility. The authors found that not wearing a helmet was associated with single vehicle crashes and collisions with another vehicle.

Webman et al. (2013)

This study was a subset analysis of a 2.5-year prospective cohort study of vulnerable roadway users injured by motor vehicles in New York City. The analysis included injured cyclists (N = 374) with known helmet status in crashes with a motor vehicle taken from Bellevue Hospital Center, a level 1 trauma center, between December 2008 and June 2011. This study aimed to evaluate the difference in the demographic information, behaviour, initial hospital evaluation and outcomes of helmeted and non-helmeted cyclists. The authors found that helmet wearing was positively related to riding with the flow of traffic and riding within bike lanes. The authors report no statistical difference in alcohol use between the two groups; however, the observed effect was not inconsequential (OR = 0.53, 95% CI: 0.22, 1.24) and in the direction opposite the risk compensation hypothesis. This study is limited by selection bias due to non-random enrolment of participants and a small sample size.

Chataway et al. (2014)

A cross-sectional study compared safety perceptions and bicycle-related behaviour of cyclists in an emerging cycling city (Brisbane, Australia) and an established cycling city (Copenhagen, Denmark). The sample consisted of 894 cyclists from Brisbane and Copenhagen recruited through university networks and cyclist forums (75% of the sample were from Brisbane).

Using structural equation modelling, the authors found that using safety gear was positively and negatively associated with the fear of traffic and distracted cycling, respectively. However, given the legislative differences (lights and reflectors are compulsory in both Brisbane and Copenhagen; helmet wearing is only compulsory in Brisbane), that authors acknowledge it is difficult to make comparisons in respect to helmet wearing and safety perceptions. In addition, there may be cultural differences in the use of bicycle helmets in the two cities. To be able to better interpret the findings of this study, the reviewers attempted to obtain separate data for each city, but they were not successful.

Martínez-Ruiz et al. (2014)

The authors used cross-sectional, crash data from Spain to examine the association of cyclists' age and sex with risk of being involved in a crash with and without adjustment for the amount of exposure. The source data was also used for (Martínez-Ruiz et al, 2013) and (Lardelli-Claret et al, 2003). For this study, the data comprised of 17,765 cyclists between 5 and 79 years old involved in one-cyclist-one-motor vehicle injury crashes between 1993 and 2009. The authors found a decrease in crashes for the youngest cyclists who were wearing a helmet and, among the youngest children, the proportion of cyclists using helmets was higher in the general population (i.e., not-responsible) than in those who were responsible for crashes. A limitation of this study includes using a quasi-induced methodology to estimate exposure.

Orsi et al. (2014)

A cross-sectional study examined factors associated with alcohol use and helmet use in Germany for years 2000–2010. In this study, the sample included 242 cyclists involved in road accidents for whom alcohol test results were available taken from the German in-depth accident study, which covers a random sample of all accidents in the municipal areas of Hannover and Dresden. A multivariable analysis with alcohol use as the dependent variable showed that non-helmeted cyclists were more than twice as likely as helmeted cyclists to be intoxicated when riding. Another multivariable analysis with helmet use as the dependent variable showed that sober cyclists were two times more likely to wear a helmet, compared to intoxicated cyclists. In addition, the authors discuss a potential selection bias since it is unlikely a cyclist involved in a traffic crash are tested for alcohol use.

Gamble and Walker (2016)

The authors conducted a laboratory experiment that compared two groups of participants (one wearing a bicycle helmet and the other group wearing a baseball cap) to examine the association between the awareness of wearing protective equipment and risk taking as well as sensation seeking. The sample was comprised of 34 males and 46 females with an average age of 25.26 years. To examine the relationship between risk taking and wearing a bicycle helmet, participants in both groups were asked to press a button to inflate an animated balloon on a computer screen. The authors found that wearing a bicycle helmet was associated with higher risk-taking scores and higher sensation seeking than wearing a baseball cap.

This study has several limitations. It is not clear how the participants were recruited or how they were assigned to groups, it is unclear if participants changed from a baseline condition, there is the potential for experimenter bias since they were not blind to treatment, and the association between helmet wearing and risk-taking behaviour was not tested in a relevant context (cycling). Additionally, sensation seeking is conceptualised as a human trait, not a state (Zuckerman, 1984). Therefore, similar to other human traits, sensation seeking does not easily vary depending on the situation (i.e., wearing or not wearing a helmet); however, this trait is generally stable over time and in different situations. A critical review of this study can be found elsewhere (Radun and Lajunen, 2018).

Lajunen (2016)

A cross-sectional self-report survey conducted in Norway aimed to compare adults' and children's reasons for wearing or not wearing a bicycle helmet. The study sample comprised 235 school children from two schools (one primary and one secondary) in the Sør-Trøndelag region in Norway and their parents (n = 106). The author found that both adults and children perceived their personal accident risk to be low and, therefore, there was no association between risk of getting seriously injured and helmet use. This study examined how wearing a helmet is related to safety feelings, instead of the association between wearing a helmet and risky behaviour. Therefore, the generalisability of the study results to the cycling population are limited.

Schleinitz et al. (2017)

A naturalistic experimental study conducted in Germany examined the association between helmet wearing and cycling speed. The sample was comprised of 76 cyclists (32 females and 44 males) and a total of 3416 trips (1902 with a helmet and 1514 without a helmet) over a four-week period. To conduct the experiment, bicycles were equipped with wheel sensors to record speed and distance as well as two cameras on the handlebar to record the cyclists' face and the forward scenery. The authors found that helmet wearing was correlated with longer trips and higher speed. However, a multiple linear regression analysis showed that helmet use had no effect on speed when controlling for other factors. This study was originally published in the proceedings of the 6th International Cycling Safety Conference. Selected papers from this conference, including this study, were later published in a special issue of the Journal of Safety Research (Schleinitz, Petzoldt and Gehler, 2018).

Salon and McIntyre (2018)

This study aimed to test the factors determining injury severity for pedestrians and cyclists using a cross-section of crash data in San Francisco, California for years 2005–2014. The data consisted of cyclists involved in a motor-vehicle collision. The authors found that 37% and 55% of helmeted and non-helmeted cyclists were at fault in the collision, respectively. That is, helmet wearers have a 52% reduction in the odds of being at fault in a crash versus non-wearers (OR = 0.48, 95% CI: 0.40–0.57). The authors also found that 78% and 83% of helmeted and non-helmeted cyclists rode on the street without a bicycle lane/path, respectively.

Fyhri et al. (2018)

This randomised crossover designed study aimed to test whether wearing a bicycle helmet is associated with faster cycling and whether this is related to a change in perceived risk. The data was collected using GPS-derived speed calculations and self-report risk perception. This was a follow up study to Fyhri and Phillips (2013) which showed a decrease in the speed of routine helmet users, but not non-routine helmet users, while cycling without a helmet. The authors posited the difference between the two groups was considered to be due to the lack of habituation (Fyhri & Phillips, 2013). The current study aimed to test whether the reduction in speed as a response to removing a helmet could be established in non-routine helmet users, after a period of habituation. The study sample consisted of 31 non-routine helmet users who were asked to complete a test route (2.4 km downhill) with and without a helmet in two phases. For the purpose of habituation, the cyclists took a 1.5–2-hour break between the two phases and were asked to ride on a predefined bicycle route while wearing a helmet. The authors found no significant difference in speed reduction before and after the break (mean speed difference for cycling with/without a helmet before the break: −0.76 km/h, 95% CI: −0.5, 2.9; mean speed difference for cycling with/without a helmet after the break: 0.32 km/h, 95% CI: −0.9, 1.5).

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