Risk Analysis DOI: 10.1111/j.1539-6924.2011.01589.x

Risk Compensation and Bicycle Helmets

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This study investigated risk compensation by cyclists in response to bicycle helmet wearing by observing changes in cycling behavior, reported experience of risk, and a possible objective measure of experienced risk. The suitability of heart rate variability (HRV) as an objective measure of experienced risk was assessed beforehand by recording HRV measures in nine participants watching a thriller film. We observed a significant decrease in HRV in line with expected increases in psychological challenge presented by the film. HRV was then used along with cycling pace and self-reported risk in a field experiment in which 35 cyclist volunteers cycled 0.4 km downhill, once with and once without a helmet. Routine helmet users reported higher experienced risk and cycled slower when they did not wear their helmet in the experiment than when they did wear their helmet, although there was no corresponding change in HRV. For cyclists not accustomed to helmets, there were no changes in speed, perceived risk, or any other measures when cycling with versus without a helmet. The findings are consistent with the notion that those who use helmets routinely perceive reduced risk when wearing a helmet, and compensate by cycling faster. They thus give some support to those urging caution in the use of helmet laws.

KEY WORDS: Bicycle; heart rate variability; helmets; risk compensation

1. INTRODUCTION

Bicycle helmets have the potential to reduce head injuries according to several cross-sectional case-control studies.[1,2] Other evidence suggests that the introduction of helmet laws does not result in clear safety effects.[3–5] One explanation given for the ambiguous effects of helmets is that cyclists perceive the risk of injury to be lower when wearing a helmet, and instinctively compensate by cycling more aggressively, according to the theory of risk compensation.[4,6,7] There is some support for this idea, with a recent study of children running over an obstacle course observing significant risk compensation in response to helmet and wrist-guard wearing.[8] However, there is no published evidence of risk compensation by cyclists in response to bicycle helmet wearing.

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The concept of risk compensation has a firm basis in the domain of driver behavior research, which typically describes how perceived risk influences various safe driving behaviors. In this tradition, risk perception is often only inferred from observed behavior or accident rates—it is rarely measured. This contrasts with research in the risk perception tradition, in which survey methods are often used to try to explain the components of risk perception, but behavioral outcomes are rarely measured.[9] The most convincing evidence for or against risk compensation would need to be gathered using a research strategy based in both traditions, that is, one that seeks to both explain the components of risk perception and link those components to associated safety behaviors.

The role of emotion in making judgments and evaluating risk has long been promoted.[10,11] It is also used by theorists in models of time-limited car driving, as well as cycling and other control of self-movement.[12] The notion of "emotional heuristics" proposes that safety margins and emotional risk work as heuristics in driving as well as in dynamic decision making in hazardous situations.[13] More recently, Vaa expanded on attempts to include emotions as a guiding principle in risk monitoring by road users.[14] Despite these accounts, there are few attempts to account for emotion as a major component of risk perceived by road users in traffic using objectively measured emotional reactions.[15]

One way to measure emotional or mental load is using psychophysiological indicators.[16] One indicator, which has been used to measure mental load in car driving, is heart rate variability (HRV).[17] HRV describes the variability in R–R intervals (effectively the time between two successive heart beats) due to the synergistic action of the parasympathetic (PNS) and sympathetic (SNS) branches of the autonomic nervous system. The balance and coordination of the PNS and SNS is not yet fully understood, but there is broad consensus that the PNS works to maintain the body at rest while the SNS mobilizes resources for action under conditions of stress or challenge.[18,19] Because deactivation of the PNS results in a decrease in HRV, a reduction in HRV is often used by researchers as an indicator of increased psychophysiological challenge.[20,21] A potential limitation of HRV is that like any psychophysiological measure, the interpretation of any changes caused by psychological challenge could be confounded by any accompanying changes due to varying physical demand.

A study finding that risk compensation cannot be detected from between-subject comparisons suggests that attempts to demonstrate risk compensation in response to a safety device should seek to measure within-subjects differences in experienced risk and safety behavior.[22] For measuring risk compensation in response to bicycle helmets, a within-subjects design also avoids problems associated with the different safety attitudes of routine helmet users compared to those of other cyclists.[23–25]

The main research question in this study was whether or not the potential safety benefits of cycle helmets are reduced by cyclists' tendency to cycle faster in order to compensate for a reduction in risk experienced when wearing them. We began in the laboratory by validating two measures of HRV as objective indicators of the emotional challenge experienced while perceiving increased risk: pNN50 and SD1/SD2,[26,27] where pNN50 is the proportion of times the change in consecutive normal sinus R–R intervals (NN) exceeds 50 milliseconds; and in the SD1/SD2 ratio, SD1 reflects the variability of successive differences between R–R intervals, and SD2 reflects the variability of the entire series of R–R intervals measurements over the longer term. Then, in a field experiment we measured within-subject differences in cycling behavior (pace), subjectively perceived risk, and HRV in volunteer cyclists cycling downhill with and without a bicycle helmet.

2. METHOD

2.1. Validation of HRV Indicators in the Laboratory

2.1.1. Using Pictures

We first attempted to measure psychophysiological response in two participants as they sat and watched a series of 60 pictures from the International Affective Picture System (IAPS), selected to elicit varying levels of emotional intensity.[28] In particular, we expected reductions in the HRV measures for pictures with IAPS reference 3000, 3120, and 3130, which have high emotional arousal according to published norms. Each test slide was presented for 6 s followed by a blank recovery slide for 15 s and then a preparation slide for 5 s. R–R interval data were collected using a wrist-watch heart rate monitor (Polar RS800cx®; Polar Electro, Norway) for 23 s following the appearance of each picture slide.

2.1.2. Using Films

R–R intervals were recorded continuously in seven participants as they sat and watched two 20-minute films presented on a large screen (*ca.* 2.5 × 2.0 m) placed 4 m away. One of the films was gently humorous (first 20 minutes of the American situation comedy *Everybody Loves Raymond*, "Debra is Sick," 1999), the other full of suspense (first 20 minutes of the American thriller film *The Hitcher*, 2007). Measures recorded during the comedy film were taken as baseline, since humorous emotional responses are reported to result in relatively little parasympathetic arousal.[29] Two additional participants were instructed to cycle gently on a stationary exercise bike while watching the films. The order of the test and control films was alternated for each successive participant in order to control for order effects.

2.1.3. Analysis

Values for pNN50, SD1, and SD2 were output automatically from the heart rate monitor data using Polar ProTrainer 5.0® software (Polar Electro, Norway). pNN10 (proportion of times the change in consecutive R–R intervals exceed 10 milliseconds) was calculated from the R–R data as necessary. In the case of the picture experiments, these measures were calculated for the fixed 23 s time interval (see above). In the case of the film experiments, the measures were calculated for the whole 20-minute period of the film or over predefined 2:20 s periods within the film. Checks were made to see whether the order of film showing was significant before proceeding to test for any differences between film types.

2.2. Cycling Pace, Self-Reported Experience, and HRV of Participants Cycling With Versus Without a Helmet

A field experiment was carried out across four weekday afternoons in September 2009 in Sognsveien, Oslo, where a cycle lane runs 0.4 km downhill to meet a busy junction (Ullevålsveien, Oslo; more details available from author on request).

To calculate the number of participants required, an *a priori* power calculation was performed assuming a large effect size (partial eta squared = 0.15). Consequently, we aimed for a sample size of $n = 35$, which gave us a power of 80% at an alpha level of 0.1. The protocol was as follows:

A first researcher stood at the side of the path, at the designated start point, and asked any passing cyclists if they would participate in an experiment. Consenting cyclists were fitted with a heart rate monitor and asked to sit and rest for 2 minutes while a baseline measure of their heart rate was recorded. The heart rate monitor continued recording until the experiment was over. One of two test bicycles fitted with a speedometer was given to the participant and the seat height adjusted accordingly. The participant was then instructed to cycle as he or she normally would, along the test route; they were not told about the purpose of the experiment. On reaching a second researcher standing at the end of the test route, each participant was asked to read and answer Survey 1 (below) and then return to the start point. Once there, the first researcher ensured that the participant rested until his or her heart rate was back at the original baseline level. The participant was then asked to cycle the test route again as he or she normally would. On reaching the second researcher for a second time, they were asked to fill out Surveys 1 and 2 (below).

Each participant was asked to wear his or her own helmet either in the first or second round of cycling. If they did not arrive with a helmet they were loaned one.

2.3. Survey 1

Survey 1 asked participants whether they had been hindered on the test route. To assess how they felt while cycling they were also asked on a 5-point scale ranging from “not at all” to “a large amount” to assess the level of (i) discomfort; (ii) excitement; and (iii) personal insecurity experienced as they cycled the test route. They were also asked to rate the actual risk for an accident (accident risk) as they cycled the test route, on a 7-point-scale ranging from “not likely at all” to “very likely.” The first researcher recorded time of day, gender, age, and whether or not the participant arrived at site wearing a helmet and subsequently used that helmet for the experiment (own helmet) and added these data to Survey 1.

2.4. Survey 2

Survey 2 instructed participants to rate how much they normally felt unsafe while out cycling (on a 7-point scale ranging from “not at all” to “very much”); the objective accident risk for cycling (on a 7-point scale ranging from “not likely at all” to “very likely”); and how much they normally use a cycle helmet (normal helmet use; on a 7-point scale ranging from “never” to “always”). There were then six questions on cycling habits addressing seasonal cycling; cycling frequency; familiarity with test route; need for speed while cycling; annoyance with other road users while cycling; and competitiveness while cycling.

2.5. Accounting for Order Effects

In the field experiment, whether a helmet was worn on the first or second trip was alternated between successive participants in order to control for order effects. In addition, a dichotomous variable order was created to denote whether the participant cycled with a helmet in the first or second round. This variable was used to account for any chance order effects during statistical analyses.

2.6. Analysis

Measurements were analyzed using Polar ProTrainer 5.0® software, which generates a plot of pace (s/km), heart rate (bpm), and R–R intervals (ms) and gives average heart rate, SD1, SD2, and pNN data for time intervals defined by the researcher.

To analyze the field experiment data, a mixed between-within subjects analysis of variance was conducted to assess the impact of own helmet (whether or not participant arrived at site wearing a helmet and subsequently used that helmet for the experiment) and normal helmet use variables on pace when cycling with versus without a helmet. To allow for comparisons with own helmet, a dichotomous variable—reported helmet use—was created for some analyses by recoding normal helmet use 1 to 3 = 0 and 4 to 7 = 1. When testing for differences according to whether or not a helmet was used on the test route, the order of the helmet wearing was controlled for by fitting order as a first step in the analysis.

2.7. Follow-Up Field Experiment

The above protocol was also used in a follow-up experiment. In this experiment, the "safe" condition was cycling with two hands on the handlebars and the "unsafe" condition was cycling with one hand on the handlebars. Data from nine participants were collected as they cycled on various circular routes in the Oslo city center, with an average distance of 0.5 km (SD 0.2 km). Data from four additional participants were collected as they cycled 0.9 km on a quiet cycle path about 3 km outside the Oslo city center, leading along Makrellbekken, downhill towards Morgedalsvegen.

3. RESULTS

3.1 Validation of HRV Measures

There were no indications of association between the percentage variation in successive R–R intervals, pNN50, or SD1/SD2 and the level of emotional arousal elicited by each IAPS test slide according to published norms. We therefore abandoned the picture experiment after testing two participants.

As expected, the SD1/SD2 for the whole 20 minutes of each film was significantly lower for the thriller than for the comedy ($p = 0.021$), but the corresponding difference in pNN50 was not significant at an alpha level of 0.05 (Table I).

Table I. Comparison of Mean Values of Psychophysiological Load Indicators Measured in Seven Participants While Viewing a Comedy and a Thriller Film (20 Minutes Each)

Film	pNN50	SD1/SD2
Comedy	10.5	0.41
Thriller	9.9	0.35
Difference	−0.6	−0.06
SED	1.87	0.025
p (1-way paired *t*-test)	0.38	0.021

In contrast, there was a significant decrease in pNN50 in line with increasing suspense over the course of the thriller film, as measured by the change from a gentle introduction period between 1:10 to 3:30 s to a period of heightened suspense between 14:10 and 16:30 s (Table II); but there was no corresponding decrease in SD1/SD2 (Table III).

However, when values for the period of heightened suspense were compared with those for the same period into the comedy film, both pNN50 and SD1/SD2 were significantly lower (Tables II and III).

For the two participants cycling while watching the films, pNN10 was chosen in favor of pNN50 because of the decrease in R–R interval lengths caused by the continuous physical demand of cycling. For both these participants the pNN values were again lower during the period of heightened suspense than during the gentler period at the start of the thriller film, falling on average from 38% to 24%, and there was also a corresponding fall in SD1/SD2, from 0.19 to 0.15, although these changes were not significant.

3.2. Cycling Pace, Self-Reported Experience, and HRV of Participants Cycling With and Without a Helmet

Of the 35 participants there were 22 men and 13 women. The average age was 30.3 years (*SD* 11.8).

After accounting for the order of the helmet wearing, there was a significant interaction between own helmet and whether or not a helmet was worn on the test route ($F(1,30) = 6.10$, $p = 0.02$) in that own helmet wearers cycled significantly faster with helmets than without, but there was no increase in speed for cyclists wearing borrowed helmets. When the interaction with own helmet was included in the model, the main effect of using a helmet on the test

Table II. Comparison of Mean Values of pNN50 Measured in Seven Participants Watching a Comedy Film Compared to a Thriller with a Pleasant Introduction Period (Between 1:10 s and 3:30 s) and a Period of Heightened Suspense (Between 14:10 s and 16:30 s)

	Time Period				
	1:10–3:30	14:10–16:30	Difference	SED	*p* (1-way paired *t*-test)
Comedy	11.4	9.5	−1.9	1.1	0.06
Thriller	13.4	6.0	−7.4	2.3	0.009
Difference	+2.0	−3.5			
SED	1.2	1.7			
p (1-way paired *t*-test)	0.08	0.044			

Table III. Comparison of Mean Values of SD1/SD2 Measured in Seven Participants Watching a Comedy Film Compared to a Thriller with a Pleasant Introduction Period (Between 1:10 s and 3:30 s) and a Period of Heightened Suspense (Between 14:10 s and 16:30 s)

	Time Period				
	1:10–3:30	14:10–16:30	Difference	SED	*p* (1-way paired *t*-test)
Comedy	0.66	0.58	−0.08	0.06	0.11
Thriller	0.47	0.36	−0.11	0.09	0.14
Difference	−0.19	−0.22			
SED	0.16	0.11			
p (1-way paired *t*-test)	0.13	0.048			

route was no longer significant. Subsequent results are therefore reported according to how much the participants were accustomed to using helmets, using the dichotomous variables own helmet and reported helmet use.

Those participants who had been cycling with their own helmet before being asked to participate, and who subsequently used that helmet for the experiment, reported increased personal insecurity and perceived that they were more likely to have an accident when they were cycling without a helmet. They also cycled significantly more slowly when not wearing a helmet (Table IV).

In contrast, those cyclists who had been cycling without a helmet before the experiment, and who subsequently borrowed a helmet for the experiment, reported little difference in personal insecurity or accident likelihood and cycled at a similar pace with and without a helmet.

Similar differences were found for the same participants grouped according to day-to-day helmet use habits (frequent or infrequent use), as shown in Table V.

Those who often used helmets reported greater discomfort, insecurity, and increased risk for an accident, and cycled more slowly without a helmet, but there were no significant differences between helmet-on and -off conditions for those who did not use helmets often.

The overall between-subject differences in pace, heart rate, pNN10, discomfort, excitement, and accident risk for infrequent versus frequent wearers (or those with vs. without their own helmets) were not significant at an alpha level of 0.05. However, those arriving with and using their own helmet reported significantly greater levels of insecurity when cycling without a helmet than those who borrowed a helmet ($SED = 0.37$; $p = 0.02$; Table IV).

The expected changes in pNN10 (higher in helmet-on condition, indicative of reduced mental load) were not observed. In fact, the pNN10 was significantly higher in the helmet-off condition for those who arrived and wore their own helmet (Table IV).

In a follow-up field experiment, in which nine participants were men, four were women, with an average age of 34.0 years (*SD* 12.9), cyclists again reported greater levels of discomfort, excitement, personal insecurity, and accident risk, and cycled more slowly in a less safe condition (this time one hand instead of two on the handlebars), as shown in Table VI.

However, even though we expected a much greater psychological challenge in the "unsafe" condition in this experiment, there was still no corresponding increase in psychological load according to the pNN10 measure, either before or after adjusting for heart rate.

Table IV. Self-Reports, Cycling Speed, and Psychophysiological Measures (Heart Rate and pNN10) Participants Cycling a Set Test Route (Distance 0.4 km) Once With and Once Without a Cycle Helmet, According to Whether the Helmet Was One They Were Using When They Were Stopped (or Borrowed from the Experimenters)

Measure	*n*	Helmet Used by Participant	Mean with Helmet	Mean without Helmet	With-Without Difference	SED	*p*-value (2-way paired *t*-test)
Pace (s/km)	17	Own	160.1	171.6	+11.5	3.9	**0.009**
	15	Borrowed	170.8	167.9	−2.9	4.3	0.52
Heart rate (bpm)	16	Own	112.6	108.5	−4.1	2.7	0.15
	14	Borrowed	110.6	113.6	+3.0	2.2	0.18
PNN10 (%)	13	Own	13.1	28.7	+15.6	6.5	**0.03**
	12	Borrowed	26.9	20.3	−6.6	4.7	0.18
Discomfort	19	Own	1.89	2.16	+0.26	0.13	0.06
	16	Borrowed	1.75	1.56	−0.19	0.19	0.33
Excitement	18	Own	2.06	2.11	+0.06	0.21	0.79
	15	Borrowed	2.33	2.27	−0.06	0.18	0.72
Insecurity	19	Own	2.11	2.79	+0.68	0.30	**0.03**
	15	Borrowed	1.80	1.87	+0.07	0.28	0.82
Accident likelihood	19	Own	2.74	3.16	+0.42	0.14	**0.007**
	16	Borrowed	2.56	2.56	0.0	0.16	1.0

Notes: Self-reports were rated on a 5-point scale where 1 = "not at all" and 5 = "a large amount," except for accident risk, which was rated on a 7-point scale where 1 = "not likely at all" and 7 = "very likely." The order of the helmet-wearing round was alternated between successive participants to control for order effects. *p* values indicating significance at an alpha level of 0.05 are indicated in bold.

Table V. Self-Reports, Cycling Speed, and Psychophysiological Measures (Heart Rate and pNN10) Participants Cycling a Set Test Route (Distance 0.4 km) Once With and Once Without a Cycle Helmet, According to Frequency of Helmet Use in Everyday Life

Measure	*n*	Reported Helmet Use	Mean with Helmet	Mean without Helmet	With-Without Difference	SED	*p*-value (2-way paired *t*-test)
Pace (s/km)	21	Frequent	161.5	170.4	+8.9	3.6	**0.02**
	11	Infrequent	172.0	168.8	−3.2	5.4	0.57
Heart rate (bpm)	20	Frequent	112.5	108.5	−4.0	1.9	0.05
	10	Infrequent	110.0	115.7	+5.7	3.3	0.12
pNN10 (%)	17	Frequent	18.3	26.9	+8.5	6.1	0.18
	8	Infrequent	22.7	19.9	−2.8	5.3	0.61
Discomfort	23	Frequent	1.83	2.13	+0.30	0.12	**0.02**
	12	Infrequent	1.83	1.42	−0.41	0.19	0.05
Excitement	22	Frequent	2.00	2.14	+0.14	0.19	0.48
	11	Infrequent	2.54	2.27	−0.27	0.14	0.08
Insecurity	23	Frequent	2.00	2.74	+0.74	0.26	**0.01**
	11	Infrequent	1.91	1.63	−0.28	0.24	0.28
Accident likelihood	23	Frequent	2.61	3.09	+0.48	0.12	**0.001**
	12	Infrequent	2.75	2.50	−0.25	0.13	0.08

Notes: Self-reports were rated on a 5-point scale where 1 = "not at all" and 5 = "a large amount," except for accident risk, which was rated on a 7-point scale where 1 = "not likely at all" and 7 = "very likely." *p* values indicating significance at an alpha level of 0.05 are indicated in bold.

4. DISCUSSION

To examine whether cyclists adapt to an increase in perceived risk when cycling without a helmet or a reduction in perceived risk when cycling with a bicycle helmet, we recorded the change in cycling pace, self-reported risk, and HRV in volunteers cycling downhill twice, once with and once without a helmet.

Laboratory work was carried out prior to the main field experiment to establish HRV as a possible objective measure of emotional challenge in cyclists. Assessment of two HRV indicators resulted in no evidence of a link between HRV and response to emotionally inducing pictures taken from a standard international picture library (IAPS). There was evidence, however, of a link between HRV and the

Table VI. Self-Reports, Cycling Speed (Pace and Time), and Psychophysiological Measures (Heart Rate and pNN10) for 13 Participants Cycling a Set Test Route (Average Distance 0.5 km) Two Times, Once with One and Once with Two Hands on the Handle Bars the Order of the One-Hand Round was Alternated Between Successive Participants to Control for Order Effects

Measure	*n*	Mean 2 Hands	Mean 1 Hand	2-Hand − 1-Hand Difference	SED	*p*-value (1-way paired *t*-test)
Pace (s/km)	11	296.2	321.0	+24.8	5.3	**0.001**
Heart rate (bpm)	11	113.7	112.9	−0.8	3.0	0.40
pNN10 (%)	11	23.3	21.9	−1.4	7.1	0.43
Discomfort	13	1.0	1.6	+0.6	0.18	**0.003**
Excitement	13	1.8	2.3	+0.5	0.14	**0.002**
Insecurity	13	1.1	1.8	+0.7	0.26	**0.005**
Accident likelihood	13	1.8	2.5	+0.7	0.26	**0.005**

Note: *p* values indicating significance at an alpha level of 0.05 are indicated in bold.

level of emotional challenge induced by a thriller film. The change in SD1/SD2 was consistent with greater mental arousal over the longer term (i.e., over the whole of a 20-minute thriller film), while the change in pNN50 was more consistent with emotional challenge over the shorter (2:20 s) film periods. The pNN measure was seen as more suitable for use in the field experiments in which any emotional challenge resulting from perceived risk would be measured over periods of between 1 and 2 minutes. A check to see whether the pNN50 measure was indicative of arousal for participants gently cycling on a stationary bicycle indicated that a related measure, pNN10, was suitable as an indicator of heightened mental arousal, even in the presence of physical load induced by gentle cycling.

In the field experiment, we observed changes in behavior (decreased cycling speed) and self-reported risk perception (increased risk associated with not using a helmet) that were in line with a theory of risk compensation in response to bicycle helmet wearing. However, these changes only occurred among cyclists accustomed to using helmets in everyday cycling. There was little change in either behavior or risk perception among those cyclists not accustomed to helmet use.

It is unlikely that the difference in helmet response between routine and nonroutine helmet wearers was due to differential practice effects because a similar number of frequent helmet wearers cycled in the helmet-on condition first and second time round. Moreover, we found that controlling for the effects of order made no difference to the conclusions taken from the analyses.

Without a helmet, infrequent helmet users cycled at a similar pace (170.4 s/km) to frequent users (168.8 s/km, Table V), but the frequent users cycled significantly faster with a helmet ($p = 0.02$). If the latter was the result of risk compensation, then one needs to explain why the infrequent helmet users neither reported reduced risk nor cycled faster when wearing a helmet in our study.

Table V shows a mean insecurity value of 1.63 for infrequent users not wearing helmets, increasing to 1.91 when they wore helmets, which is less than the insecurity of frequent helmet users (2.0 with and 2.74 without helmets). The means for discomfort have the same ranking, least (1.42) for infrequent wearers without helmets, higher for both groups wearing helmets (1.83), and highest of all for frequent users without their helmets. This suggests that both comfort and security influence the choice of whether to wear a helmet. Cyclists who already feel secure and those who find helmets uncomfortable are unlikely to wear them, and so would fall into the infrequent users category. In our study, infrequent users did not feel more secure when wearing a helmet. Feelings of discomfort are likely to increase insecurity, and this may have counteracted the increased security that would otherwise have been expected from helmet wearing. Consequently, no risk compensation would be expected. In contrast, the cyclists who wore helmets by choice felt more comfortable and secure when wearing them, and as predicted by the theory of risk compensation, cycled more slowly when not wearing a helmet.

An important limitation of our study is that it does not consider the dynamics of risk adaptation in response to helmet wearing. In other words, we do not know whether the discomfort and insecurity felt by infrequent users when wearing a helmet would have reduced over time, nor do we know how long it took routine helmet wearers to feel more secure and comfortable wearing helmets in the first place. A previous finding that nonhabitual seatbelt wearers increase unsafe driving behaviors over the course of a year after beginning to wear a seatbelt suggests that helmet wearing may increase risk-taking behavior over the longer term.[30] Both driving and cycling are complex learned behaviors that may change gradually over time in response to an increased sense of security.

Note also that a recent study characterizes a subpopulation of "sporty" cyclists who cycle aggressively and tend to use safety equipment as part of their cycling identity.[25] If this type of cyclist was overrepresented in the routine helmet user group in our study, then the significant difference in effect of helmet on pace observed between routine and nonroutine helmet users may have been more due to innate group characteristics than generic long-term risk compensation. That said, the differences in risk and behavior observed within routine user participants across the helmet-on and -off conditions remains in line with a theory of risk compensation by this group.

Whatever the dynamics and confounders of risk compensation, the most important issue for policymakers and planners remains whether helmet use should be encouraged or not. The data in this article show that cyclists accustomed to helmets may either cycle faster with the helmet on or may slow down when the helmet is taken away. Whether cyclists would continue to cycle more slowly without a helmet is uncertain, but the possibility remains that helmet laws may increase cycling speed among certain cyclists, while discouraging those who find helmets uncomfortable from cycling. Given the association between speed and risk of accidents, this might even explain reports that helmets and helmet laws have not been shown to reduce the risk of injury per cyclist.[5,31]

Attempts to build on the findings of this exploratory study should attend to its methodological limitations. First of all, the sample sizes used in the field experiments were designed to give 80% chance that we would find a within-subject difference, a power level considered marginal. Further experiments to repeat our findings might obtain more robust results by using increased sample sizes. A further limitation of the field studies was that the number of respondents varied somewhat for each measure. Some questions on the survey were accidentally skipped by the participants, leading to some missing data for the self-report measures, while in other cases physiological data collection was not possible because the chest-strap detector of the pulse monitor did not always fit the participant sufficiently; some of the pace data were lost because the wrist-strap device failed to receive the data transmitted by the bicycle's speedometer. We did not make adjustments in the statistical analysis, since the missing data were limited for most measures (see Tables IV and V). We should point out, however, that for the measure for which missing data were most pronounced—the objective pNN10 measure—our ability to detect a significant difference would have been reduced.

Notwithstanding these limitations, those changes in experienced risk reported by participants were not reflected by changes in our selected measure of emotional challenge, pNN10. Even when we attempted to increase the level of psychological challenge in a follow-up study, by asking participants to cycle without a helmet using one versus two hands, there was no change in pNN10 despite increased differences in cycle pace, discomfort, excitement, personal insecurity, and accident risk between conditions (Table VI). In both main and follow-up field experiments, however, we could not be certain that any differences in psychological challenge measured by the HRV indicator were not masked by variations in physical load within or across participants, even though we hoped that the downhill gradient would minimize any such effects. Increased cycling speed in the absence of a helmet was associated with increased heart rate and reduced pNN10, which implies that participants varied their speed using the pedals, rather than the brakes as we had envisaged. We attempted to account for the confounding effect of varying physical load on pNN10 as a measure of mental load by multiplying it by heart rate, but this new measure of emotional challenge was linked neither to self-reported risk nor helmet wearing.[1]

Another explanation for the lack of observed change in psychophysiological measures is that participant self-reports and cycling speed might have been the result of cognitive rather than emotional processing.[32] In line with the "zero-risk theory" of Näätänen and Summala,[12,33–35] helmet users may have kept full subjective control over their riding in both conditions, such that no physiological response concomitant to a cognitively reasoned speed decrement occurred.

5. CONCLUSIONS

Our results show increased cycling speed and decreased risk perception in a helmet-on compared to a helmet-off condition among cyclists used to wearing helmets, a finding that is in line with the theory

[1] The variable used was (pNN10 × heart rate)/100.

of risk compensation. However, for those cyclists not used to helmets there were no differences in either risk or behavior between the helmet-off and helmet-on conditions. We recommend that future researchers (i) devise ways to control physical load placed on cyclists in realistic settings, in order to be able to better study the role of mental load or emotion in risk compensation; and (ii) better consider the dynamics of risk compensation.

ACKNOWLEDGMENTS

The study was funded by the Norwegian Research Council as part of the program Risk and Safety in Transport (RISIT).

REFERENCES

1. Thompson DC, Rivara FP, Thompson R. Helmets for preventing head and facial injuries in bicyclists. Cochrane Database of Systematic Reviews, 2000; 2000(2):CD001855.
2. Attewell RG, Glase K, McFadden M. Bicycle helmet efficacy: A meta-analysis. Accident Analysis & Prevention, 2001; 33(3):345–352.
3. Towner W, Dowswell T, Burkes M, Dickinson H, Towner J, Hayes M. Bicycle Helmets—A Review of Their Effectiveness: A Critical Review of the Literature. London, UK: Road Safety Research Report, 2002, Department for Transport, 2002.
4. Robinson DL. No clear evidence from countries that have enforced the wearing of helmets. British Medical Journal, 2006; 332:722–725.
5. Elvik R. Publication bias and time-trend bias in meta-analysis of bicycle helmet efficiency: A re-analysis of Attewell, Glase and McFadden, 2001. Accident Analysis & Prevention, 2011. doi: 10.1016/j.aap.2011.01.007.
6. Adams J, Hillman M. The risk compensation theory and bicycle helmets. Injury Prevention, 2001; 7(4):343.
7. Robinson DL. Do enforced bicycle helmet laws improve public health? No clear evidence from countries that have enforced the wearing of helmets. British Medical Journal, 2006; 332:722–725.
8. Morrongiello BA, Walpole B, Lasenby J. Understanding children's injury-risk behavior: Wearing safety gear can lead to increased risk taking. Accident Analysis & Prevention, 2007; 39(3):618–623.
9. Wåhlberg A. The theoretical features of some current approaches to risk perception. Journal of Risk Research, 2001; 4(3):237–250.
10. Zajonc RB. Feeling and thinking—Preferences need no inferences. American Psychologist, 1980; 35:151–171.
11. Finucane ML, Alhakami A, Slovic P, Johnson SM. The affect heuristic of making judgments of risks and benefits. Journal of Behavioral Decision Making, 2000; 13(1):1–17.
12. Näätänen R, Summala H (eds). Road-User Behaviour and Traffic Accidents. New York: American Elsevier, 1976.
13. Summala H. Modeling driver behaviour: Pessimistic prediction? Pp. 43–65 in Evans L, Schwing RC (eds). Human Behaviour and Traffic Accidents. New York: Plenum, 1985.
14. Vaa T. Survival or deviance? A Model for Driver Behaviour. Final report. Report number 666/2003. Oslo, Norway: Institute of Transport Economics, 2003.
15. Mesken J. Measuring Emotions in Traffic. Leidschendam: SWOV, 2002.
16. De Waard D. The Measurement of Drivers' Mental Workload. Traffic Research Centre, VSC: Haren, 1996.
17. Cnossen F, Rothengatter T, Meijman T. Strategic changes in task performance in simulated car driving as an adaptive response to task demands. Transportation Research Part F: Traffic Psychology and Behaviour, 2000; 3(3):123–140.
18. Goldberger JJ, Challapalli S, Tung R, Parker MA, Kadish AH. Relationship of heart rate variability to parasympathetic effect. Circulation, 2001; 103:1977–1983.
19. Brodal P. The Central Nervous System: Structure and Function. 3rd edition. US: Oxford University Press, 2004.
20. McCraty R, Barrios-Choplin B. The impact of a new emotional self-management program on stress, emotions, heart rate variability, DHEA and cortisol. Integrative Physiological and Behavioral Science, 1998; 33(2):151–170.
21. Papousek I, Nauschnegg K, Paechter M, Lackner HK, Goswami N, Schulter G. Trait and state positive affect and cardiovascular recovery from experimental academic stress. Biological Psychology, 2010; 83(2): 108–115.
22. Streff FM, Geller ES. An experimental test of risk compensation: Between-subject versus within-subject analsyes. Accident Analysis & Prevention, 1988; 20(4):277–287.
23. Lajunen T, Rasanen M. Can social psychological models be used to promote bicycle helmet use among teenagers? A comparison of the health belief model, theory of planned behavior and the locus of control. J Safety Res, 2004; 35(1):115–123.
24. McGuire L, Smith A. Cycling safety: Injury prevention in Oxford cyclists. Injury Prevention, 2000; 6(4):285–287.
25. Fyhri A, Bjørnskau T, Backer-Grøndahl A. Bicycle helmets—A case of risk compensation? Transport Research—Part F, 2010.
26. Tulppo MP, Makikallio TH, Seppanen T, Laukkanen RT, Huikuri HV. Vagal modulation of heart rate during exercise: Effects of age and physical fitness. American Journal of Physiology Heart Circulatory Physiology, 1998; 274(2):H424–H429.
27. Karmakar CK, Khandoker AH, Gubbi J, Palaniswami M. Complex correlation measure: A novel decriptor for Poincaré plot. BioMedical Engineering Online, 2009; 8:17.
28. Lang PJ, Bradley MM, Cuthbert BN. International Affective Picture System (IAPS): Affective Ratings of Pictures and Instruction Manual. Gainesville, FL: University of Florida, 2008.
29. Myrtek M, Brugner G. Perception of emotions in everyday life: Studies with patients and normals. Biological Psychology, 1996; 42:147–164.
30. Janssen W. Seat-belt wearing and driver behaviour: An instrumented-vehicle study. Accident Analysis & Prevention, 1994; 26:249–261.
31. Robinson DL. Head injuries and bicycle helmet laws. Accident Analysis & Prevention, 1996; 28:463–475.
32. McKenna FP. The human factor in driving accidents: An overview of approaches and problems. Ergonomics, 1982; 25: 867–877.
33. McColgan J, Nash D. Findings from international railway roster studies—Moving beyond fatigue management limitations of current schedule design: A three-prong approach, in International Conference on Fatigue Management in Transport Operations. A Framework for Progress. Boston, MA: US Department of Transportation, 2009.
34. Summala H. Risk control is not risk adjustment: The zero-risk theory of driver behaviour and its implications. Ergonomics, 1988; 31:491–506.
35. Summala H. Towards understanding motivational and emotional factors in driver behaviour: Comfort through satisficing. Pp. 208–232 in Cacciabue PC (ed). Modelling Driver Behaviour in Automotive Environments—Critical Issues in Driver Interactions with Intelligent Transport Systems. London: Springer Verlag, 2007.