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Analysis of Heart Rate Variability amongst Cyclists under Perceived Variations of Risk Exposure

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Abstract

Cycling as a mode of travel provides an opportunity for many people to increase their levels of regular physical activity and contribute to their mental and physical health. Heart rate is often used as a means of measuring the intensity and energy expenditure of physical activity. However, heart rate is also linked to emotional factors such as anxiety and fear. Perceptions of risk due to external factors such as other road users and infrastructure may arouse such emotions in urban cyclists. The present study set out to investigate whether or not perceptions of risk among urban cyclists may lead to increased heart rates. Cyclists completed a test route in normal traffic conditions in Cork, Ireland and heart rates and self-reported risk ratings were recorded in real time. Evidence was found of a link between perceptions of risk and heart rates. This raises questions regarding the use of heart rate to estimate exercise intensity and energy expenditure during urban cycling. The perceptions of cyclists of their safety in relation to various road elements on familiar routes were also assessed, as well as specific events which they perceive to be high in risk. The results indicate that incidents involving car traffic and busy roads which offer no protection from interaction with car traffic are associated with greatest perceptions of risk.

1 Introduction

Incorporating cycling into daily routine is increasingly being recognised as an effective means of increasing physical activity levels (Cavill et al., 2008, Kahlmeier et al., 2010, Rutter et al., 2013). Regular physical activity is a major contributor to physical and mental health and promotion of active travel has been identified by WHO Regional Office for Europe as a supporting intervention for the prevention and control of non-communicable diseases (WHO, 2011). However, in order to ensure that any programme of increased physical activity brings health benefits, both the quantity and quality of exercise taken should be considered. The American College of Sports Medicine (ACSM) has published specific recommendations regarding both intensity and total energy expenditure of exercise for maintaining fitness (Garber et al., 2011). It is well established that heart rate (HR) increases linearly with oxygen consumption (VO_2) (ACSM, 2011, Åstrand, 1976, Åstrand et al., 2003, Bassett et al., 2012). Based on this principal, the ACSM has also identified optimum HR zones for various levels of exercise intensity (Garber et al., 2011) and a leading HR monitor manufacturer has published cycling specific HR zones (Polar, 2013). Activity energy expenditure (AEE) can also be estimated based on a linear relationship with HR (Bassett et al., 2012).

There are many commercially available HR monitors that are used during cycling and other exercise routines in order to target specific HR zones and calculate AEE. However, HR may be elevated by emotional and environmental factors which could produce non-linearities in the relationship between HR and oxygen consumption (VO_2) (Åstrand et al., 2003, Crouter et al., 2008). It has been suggested that the combination of HR monitoring and movement registration may improve estimates of AEE (Brage et al., 2004). Some devices attempt to do this by using both HR monitors and accelerometers. An evaluation study compared AEE estimated by one such monitor using a combined activity and HR algorithm to a reference AEE calculated from measured VO_2 and carbon dioxide consumption (VCO_2), for 18 activities (Crouter et al., 2008). The AEE estimations calculated by the combined activity and HR algorithm differed significantly from the reference values for 3 of the 18 activities. Also, none of the activities studied would have been likely to arouse fear or anxiety.

It is recognised that feelings of fear and anxiety may be associated with increased HR. In 1992, a major study (Levenson, 1992) studied the differences in autonomic nervous system (ANS) responses between different emotions. Large increases in HR were consistently found in response to a variety of fear inducing stimuli. Cacioppo (2000) later performed a meta-analysis across 22 studies on the question of whether there are emotion-specific physiological patterns. It was found that fear was associated with higher HR responses when compared to happiness, sadness or disgust. Levenson (1992) suggests that that the association of fear with increased HR may reflect a close association of fear with the motor program of “flight” . The “flight” response, described in detail by Cannon (1929), refers to the fear induced bodily responses which prepare an organism for the great exertions which may follow. A more recent study of drivers’ emotions found that anxiety, but not anger or happiness, was associated with increased perceptions of risk and with increased HR (Mesken et al., 2007). Another recent study (Lerner et al., 2005) studied differences in HR responses to anger and fear in participants performing a difficult arithmetic task. Fear was positively correlated with HR, whereas anger was negatively correlated with HR. All this evidence indicates that if an activity arouses feelings of fear or anxiety, these emotions may have an increasing effect on HR.

Several recent studies have suggested that cycling is perceived by transport users as being an unsafe mode of transport, particularly in an urban commuting environment where cyclists are exposed to motor vehicle traffic (Lawson et al., 2013b, Winters et al., 2012, Winters et al., 2011). The perceptions of safety by cyclists are influenced by a wide range of factors such as age, regularity of cycling, road type and attitudes of vehicle drivers (Lawson et al., 2013b). Individual events such as conflicts with other road users and near misses are likely to be perceived as particularly high in risk but there is little information available in relation to these types of events. This implies that cyclists are likely to experience varying levels of fear and anxiety due their perceptions of risk while cycling in a mixed mode network and it can reasonably be expected that this fear and anxiety may lead to variations in their HR. Also, there is no evidence to suggest that any currently available HR-based exercise intensity or AEE measurement devices are capable of compensating for the effects of significant levels of fear and anxiety. Therefore, the perceptions of risk among cyclists in a mixed more urban environment may cause miscalculation of exercise intensity and AEE as measured by the aforementioned devices.

The present study aimed to investigate the relationship between HR and perceptions of risk among cyclists. Evidence of a link was demonstrated, showing that the response of cyclists to situations which are perceived as being high in risk is not just psychological but physiological also. The link between risk perceptions and HR may be an indication of the "flight" response which is typically accompanied by other physiological responses such as a release of adrenaline. The link between risk perceptions and HR also raises questions regarding the accuracy of devices which rely on HR for evaluation of the benefits of exercise in the context of active travel.

Recent evidence has also shown that there is disagreement between cyclists' perception of the safety of particular road elements and actual safety and that perceptions of safety have more influence on cycling modal share than actual safety (Dill and Voros, 2007, Keegan and Galbraith, 2005, Noland, 1995, Parkin et al., 2007, Winters et al., 2012). Previous researches into perceptions of risk among cyclists have used methods such as site interviews (Moller and Hels, 2008), video clips (Klobucar and Fricker, 2007, Parkin et al., 2007), test courses (Landis et al., 1997, Landis et al., 2003), surveys (Lawson et al., 2013b, Leden et al., 2000) and simulations (Hughes and Harkey, 1997). With the exception of Lawson et al. (2013b), the tests mentioned above focus on specific sites, (with which the participant may or may not be familiar) and consider a small number of variables. They are also conducted over short time frames and so, the likelihood of a particularly high risk event such as a near miss occurring is low. One case-crossover study addressed these limitations by recruiting cyclists who had sustained an injury while cycling, but since participants were recruited based on hospital records; minor injuries and near misses were not captured (Winters et al., 2012). The present study addresses the limitations of previous studies by exploring the risk perceptions of each individual cyclist in relation to their regular route. Each route is characterised into discrete road elements so that the cumulative experiences of the cyclists with respect to each type of road element can be studied. Another key contribution of this study is the ability to capture and characterise any specific event which may be perceived by a cyclist as being high in risk, such as a conflict or near miss.

The next section of this paper describes the methodology employed in each element of the study. This is followed by a presentation of the results observed, a discussion of those results and finally, the conclusions which may be drawn.

2 Methodology

2.1 Design of Experiments

The study was comprised of a fully controlled experiment, a partially controlled experiment and an uncontrolled experiment.

2.1.1 Fully Controlled Experiment

In the fully controlled experiment, HRs of participants were measured while completing various trials in an environment isolated from all forms of traffic where the effects of feelings of insecurity were expected to be negligible.

Each trial lasted approximately 10 seconds and consisted of a short approach followed by a manoeuvre and a short home straight. Different course types and difficulties were used with three levels for each course type and difficulty level. The three course types; slalom course, cornering course and gap course are illustrated in Fig. 1. The three levels of difficulty (L1, L2 and L3) were set by adjusting the between-cone distance, the corner radius and the gap width respectively. The difficulty levels were chosen in order to capture a range of difficulty levels within each course type. The levels may not have been comparable between different course types. Each participant completed nine trials in total. The three course types were completed in a random order in order to control the effect of any improvement in skill or comfort of infrequent cyclists during the trials. Within each course type, the trials were completed in order of increasing difficulty.

Participants were instructed to complete each trial at a comfortable pace and were given a rest of at least one minute between trials in order to ensure that their HR had returned to a normal resting rate before beginning the next trial.

2.1.2 Partially Controlled Experiment

In the partially controlled experiment, participants cycled two fixed routes in Cork city while exposed to normal traffic conditions. Route 1 (anti-clockwise) is shown in Fig. 2 and route 2 was a clockwise version of the same journey, beginning and ending at the same point. The lengths, road classes and Annual Average Daily Traffic (AADT) of each road section encountered on the routes are shown in table 1. AADTs were calculated from short term traffic counts using the NRA Permanent Counter Method (National Roads Authority, 2012a) where possible and the NRA Generic Expansion Factor Method (National Roads Authority, 2012b) otherwise. No traffic count data were available for one of the road sections, Gaol Walk. Each route was approximately 2.7 km long and took between 9 and 15 minutes to complete depending mainly on traffic signalling. HRs were measured continuously throughout the experiment. At scheduled locations along each route, participants were instructed to announce a number between 1 and 10 to represent the degree to which they felt at risk, based on the risk rating scale in table 2 (a). A risk rating of 1 would denote “Very Little Risk” and a risk rating of 10 would denote “Risk of Severe Accident”. The participants, who were all residents of the study area, were informed of the locations of the scheduled rating points before beginning the routes. The audio recording of the head mounted camera captured the risk ratings announced by the participants and the video recording allowed the authors to identify the location and context associated with the risk rating. Since the Real-Time-Clocks of both the HR monitor and video camera were synchronised, the data from both could be related. Twelve scheduled rating points were chosen on each route to include a variety of road elements (intersections, T-junctions, roundabouts, advanced stop lines, bus lanes, narrow roads, poor road surfaces) and manoeuvres (right/left turns, intersection crossing, lane changes, merging).

2.1.3 Uncontrolled Experiment

2.1.3.1 Travel Diaries

As part of the uncontrolled experiment, participants completed their normal cycling routine over the course of one week and completed a log entry in a cycling diary after each journey. Participants were instructed that each diary entry should include any note-worthy incidents such as: accidents, near-accidents, collisions of any kind or any other incidents which caused a notable reaction or change in risk perception. For each incident reported, the participant was required to give a risk rating on the 10 point scale in table 2 (a), ranging from "Very Little Risk" to "Risk of Severe Accident" and a culpability rating on the 10 point scale in table 2 (b), ranging from "Other Completely at Fault" to "Self Completely at Fault".

2.1.3.2 Road Element Type Surveys

Participants of the uncontrolled experiment also filled out a road element type survey. This required them to characterise their regular route into a sequence of road elements. The choice of road elements was limited to a list which was adapted for this study from a list used in a previous study (Parkin et al., 2007). It was noted to participants that not every possible road element type was included in the list and so, not every element on their own route necessarily needed to be reported. Participants then gave a risk rating for each road element on the 10 point scale in table 2 (a).

2.2 Equipment

All participants used their own bikes and were required to wear a cycle helmet and reflective jacket at all times during both the fully controlled and partially controlled experiments. The cyclist configuration can be seen in Fig. 3 (a).

2.2.1 Heart Rate Monitor

The heart rate monitor worn by all participants during both the fully controlled and partially controlled experiments was a "Suunto memory belt"; a lightweight plastic belt which is worn around the chest and detects HR by means of by two thin electrode strips making contact with the chest. The location of the heart rate monitor can be seen in Fig. 3 (a). The HR is calculated from the Interbeat interval (IBI), measured in milliseconds. After the experiments were carried out, the HR data were transferred to a computer using a docking station and analysed.

2.2.2 Head Mounted Camera

During the partially controlled testing only, participants wore a "Sports Action Helmet Head Camera" which was secured by a strap around their head and pointed directly in front of their face in order to capture their frame of view. The camera can be seen in Fig. 3 (b).This camera is capable of recording footage at 640 x 480 VGA resolution and 30 frames per second or at HD720P (1280 x 720) resolution and 24 frames per second. The camera records sound through a built-in microphone. The audio and video recordings captured the announced risk rating and associated location for each scheduled rating point.

2.3 Participants

For the fully controlled and partially controlled elements of this study, 13 volunteers were recruited from University College Cork using noticeboard advertisements and the authors' networks. All 13 volunteers were 23 year old males. This homogeneity of age and gender in the study group was intentional. A study representing all social and demographic groups without bias could only have been achieved through the recruitment of a huge randomised sample including non-residents of

Ireland. This would be warranted if there were a previously validated methodology which could be used. The purpose of the current study was to develop and validate such a methodology. In order to guard against sources of variability which might obscure genuine, if small, effects; the scope of the study was deliberately restricted to the most common cyclists in Cork city—young males in the age group 20 – 25 years (Lawson et al., 2013a). This limited the impact of differences in certain personal characteristics on the results, albeit at some cost in terms of generalizability. Each participant completed a short questionnaire, the results of which are outlined in table 3. All 13 volunteers participated in the controlled experiment and 8 volunteers participated in the partially-controlled experiment. As per the responses to the questionnaire, the participants were of varying degrees of physical fitness and cycling experience. As a within-subject design was used for the study and so, differences between subjects were not of interest, a small study group was appropriate. This is consistent with other within-subject studies of transport behaviour (Beanland et al., 2013, Benedetto et al., 2013, de Waard et al., 2011, Ho et al., 2005, Van Erp and Van Veen, 2004). The length of the course and number of rating points were the most important factors in relation to the statistical power of the partially controlled experiment. A total of 180 risk rating and HR pairs were recorded over approximately 40.5 km (15 completed routes x 2.7km each) of cycling.

For the uncontrolled experiment, surveys were distributed to 39 volunteers, including students and staff of UCC as well as members of the public service. 20 completed surveys were received from male volunteers between the ages of 22 and 24.

3 Results

3.1 Controlled Experiment

Each subject completed each of the nine trials described in section 2.1.1. Generally, the subjects' HRs showed a steady increase throughout the test, with a peak just before the end. Figure 4 shows a typical result; the evolution in HR for subject, SC during the three Gap tests. During the level 3 trial, there was a clear outlier which may have resulted from a momentary equipment malfunction. In order to reduce the effect of such extreme outliers, median HRs were considered in the following analysis. The distribution of median HRs for each task type and difficulty level is shown in Fig. 5.

A two way analysis of variance with interaction was carried out on median HR against course type and difficulty level. This showed a non-significant main effect of course type on median HR with $F(2,117)=0.85$, $p=0.43$. The main effect of difficulty level on HR approached conventional levels for significance, ($F(2,117)= 2.81$, $p= 0.06$). It is worth noting that despite this, the effect size (0.05), as quantified by partial eta-squared (Pierce et al., 2004), indicates that the effect was small, rather than that no effect was present (Cohen, 1988). There was, however, a significant ($\alpha=0.05$) interaction effect between course type and difficulty level on median HR ($F(4,117)=3.03$, $p=0.02$). The source of this interaction may have been that the impact of the difficulty level on exertion and HR was not constant across the course types.

3.2 Partially Controlled Experiment

3.2.1 Risk Ratings

The partially controlled test was completed by 8 participants in the anti-clockwise direction (Route 1) and 7 participants in the clockwise direction (Route 2). Risk ratings for each of the scheduled rating points were determined for each participant by examination of the video and audio recordings. As there were twelve rating points on each route, a total of 180 ratings were obtained. The risk rating data had a sample mean of 2.47 and a sample standard deviation of 1.21. As shown in Fig. 6, the most common risk rating was 2. The highest risk ratings had the lowest frequencies. Risk ratings of 7, 9 and 10 had frequencies of 0.

3.2.2 Heart Rate and Risk Rating

As the video camera clock and heart-rate monitor clock were synchronised, it was possible to obtain the instantaneous HR reading at the time of each risk rating. Fig. 7 shows a sample of a participant's recorded HR and risk ratings during the anti-clockwise course (Route 1). Some sudden spikes in HR data can be seen which are not representative of realistic HRs and may have resulted from measurement issues such as a momentary loss of electrode contact. These were ignored.

In order to investigate the relationship between HR and risk rating, the HR data was divided into groups based on the associated risk ratings. A box and whisker plot of the HR data grouped by risk rating is displayed in Figure 8. The plot appears to reveal a linear trend between HR and risk rating but the pattern is equivocal. The relationship between HR and Risk Rating was further investigated by performing Analysis of Variance of the HR data and considering Risk Rating as a treatment. However, a One Way ANOVA of HR against Risk Rating would fail to recognise if the relationship between subjective risk perceptions and HR was different for different subjects, as would reasonably be expected. Therefore, each individual's combination of personal characteristics was also considered as a treatment. Accordingly, Two Way Analysis of Variance was carried out, considering the reported risk ratings and the individual participants as treatments, and the HR recorded at each rating point as the repeated measure. No risk ratings of 7, 9 or 10 had been recorded and the data pairs with risk ratings of 6 and 8 were discarded as their variances were trivial. The results of the Two Way ANOVA showed a significant dependency between HR and Risk Rating ($F(4,141)=2.7$, $p = 0.03$), indicating that the variance in HR between the risk rating groups was significantly greater than the variance in HR within those groups. Therefore, it is possible to reject the null hypothesis that the difference in average HR between the risk rating groups was merely due to chance (i.e. that Risk Rating and HR are independent of one another).This does not necessarily infer that as Risk Rating increases, so does HR but it does show that the HRs for at least two of the risk rating groups appear to come from populations with statistically different means. There was also a significant dependency between HR and the individual participant ($F(7,141)=15$, $p=1.54e\text{-}14$) as would be expected. However, there was a non-significant interaction effect of the two treatments, Risk Rating and individual participant, on HR ($F(24,141)= 0.77$, $p=0.77$). Therefore, the null hypothesis of no interaction — that the differences in HR under the categories of one treatment are not different for any two categories of the other treatment — cannot be rejected (Kirk, 1995). What this indicates is that, although HR was dependent on both the individual and their risk rating, the systematic differences in HR associated with different risk ratings were similar among different individuals.

The Student-Newman-Keuls (SNK) method was used to perform pairwise comparisons between the means of the risk rating groups. At the 5% significance level, SNK divided the risk rating groups into two sets which were statistically different from one another; one containing the risk rating groups 1, 2, 3 and 4 and the other containing the risk rating groups 3 and 5. The results are shown in table 4. This implies that the mean of risk rating group 5 was significantly higher than the means of risk rating groups 1, 2, and 4 at the 5% significance level. The inclusion of risk rating group 3 in both sets indicates that its mean was not statistically different from the means of either set.

3.2.3 Within risk-rating distributions of HR

Due to the relative sparsity of HR data with risk ratings of 4 and above, the HR data were considered in risk ratings groups of 1, 2, 3 and 4+ (RR1, RR2, RR3 and RR4 respectively) according to the reported risk rating associated with each recorded HR. The HR distribution within each risk rating group could then be examined. Table 5 summarises the properties of the 4 probability distribution function (PDF) curves. The variance of the HR data was highest for RR2. The RR1 HR data were slightly positively skewed whereas the RR2, RR3 and RR4 HR data were negatively skewed. All 4 data sets were mildly platykurtic. The moderate values of skewness and kurtosis for all 4 groups are suggestive of normal populations.

It can be seen from Fig. 9 that the HR distributions for all risk rating groups were approximately normal. The distributions were further tested for normality using the Lilliefors test, Anderson-Darling test, Jacques-Bera test and Shapiro-Wilk test (Cromwell et al., 1994, Royston, 1982, Stephens, 1974, Thode, 2002). All distributions passed each of these tests except for the RR2 data which failed the Shapiro-Wilk test (p= 0.03432) due to the relatively high negative skew. The kernel density weighed curves, histograms and approximate normal density curves for each group are shown in Fig. 10. The sample mean and sample variance of each risk rating group were used to generate the normal approximations.

3.2.4 HR Zones

In order to illustrate the effect of risk rating on HR using a discretised approach, the HR data were categorised into 5 HR zones, as recommended in "Polar Sport Zones for Cycling" (Polar, 2013). A 6th zone, $HR_{Recovery}$, was added to capture HRs below 50% of maximum HR (HR_{max}). HR_{max} for each participant was calculated using equation 3.1 (Gerstenblith et al., 1976)

$$HR_{max} = 220 - a \tag{3.1}$$

where a is the age of a participant. The probability of each HR zone was then calculated as $P\{C_1 \leq HR < C_2\}$ where C_1 and C_2 for each HR zone are defined in table 6.

The probability of a HR falling in each zone was then calculated for each Risk Rating group by integrating the kernel density weighed approximation of the PDF. For RR1, the HR zone with highest probability is the Light zone. For RR2, the probability of the Light zone is significantly decreased and the probabilities of the Hard and Maximal zones are increased. For RR3, the probability of the Light zone is again decreased with an increase in probability of the Moderate, Hard and Maximal zones. RR4 carries similar probabilities to RR3 with a slightly lower probability of Hard and Moderate zones and slightly higher probabilities of Very Light and Light zones.

3.3 Uncontrolled Experiment

3.3.1 Travel Diaries

In total, there were 57 incidents recorded, 38 of which were deemed relevant to the study. The recorded incidents were inspected systematically by the researchers with the aim of finding common themes. It was found that the recorded incidents could be divided into 12 incident types. Table 7 shows the frequency and the average risk rating and culpability rating for each incident type. The standard deviation for the average risk ratings was 1.5. The incident types with the highest risk rating were “Near head on collision”, “Car door opened in front of cyclist “and “Car turning right across cyclist at junction”. The standard deviation for the average culpability ratings was 0.7 and, on average, the cyclists admitted the highest culpability for incidents with pedestrians.

3.3.2 Road Element Type Surveys

Table 8 summarises the results of the road element type survey. The road element types with the highest average risk ratings were busy roads without a bicycle lane (5.08) and roundabouts where the cyclist continued straight on (5.04). The road element type with the lowest average risk rating was off-road cycling path (1.06). The standard deviation of the average risk ratings was 1.12. In order to test the consistency of risk ratings between different participants; for each road element, the average risk rating given by each participant and the standard deviation of those averages were also calculated. They are displayed in Table 8.

4 Discussion

4.1 Fully Controlled Experiment

As expected, HR rose throughout most of each trial since participants started from rest and the trials were too short for HR to reach a steady state. The dip in HR before the end of each test reflected the point where the manoeuvre had been completed and the participant was only required to cycle straight until the finish line. No notable sharp jumps or erratic variations were seen. There is a stark contrast between this and the irregularity of the HR data from the partially controlled experiment, even after removing outliers caused by measurement error. This suggests a strong influence of the exposure to traffic on variation of HR which could be due to greater perception of risk or the greater physiological effort required while cycling in traffic or a combination of both.

The results of the controlled experiment suggest a complex relationship between type of manoeuvre, difficulty level and HR. It can be seen from Fig. 5 that, for the gap and slalom tests, median HR increases with increasing difficulty. However, for the corner test, the median HR decreases with increasing difficulty. It is not clear, however, whether this was due to the fact that a smaller radius effectively makes the manoeuvre shorter and allows less time for the HR to increase. It is possible that if this change in length had been controlled for, higher difficulty levels would have been associated with higher HRs in the corner test as well. The results of the 2-Way ANOVA with Interaction of HR against course type and difficulty level substantiate this observed complex relationship.

4.2 Partially Controlled Experiment

Based on the variability of the risk ratings reported by participants in the partially controlled testing ($\bar{x}$ =2.47, s=1.21), it can be inferred that perceptions of risk cannot realistically be considered to remain constant throughout a cycling trip. Therefore, studies which use a constant per-unit -distance cost of risk perceptions (Sælensminde, 2004) may be over-simplifying in their analysis and more detailed modelling of perceptions of risk may produce more accurate results.

The main finding of the partially controlled experiment is that there is a significant dependency between perceptions of risk among cyclists and HR. The frequencies of risk ratings above 5 were too low to make any inferences about the HRs associated with these risk ratings. However, as shown in Fig. 8, for risk ratings of 1 to 5, higher risk ratings were generally associated with higher HRs. The observed link between risk rating and HR is confirmed by the two-way ANOVA with interaction of HR against risk rating and individual participant. The SNK post-hoc test produced a more conservative result, suggesting that the only statistically significant difference in means at the 5% significance level was between risk rating group 5 and risk rating groups 1, 2 and 4. This implies that only high risk perceptions have a significant effect on HR. However, it is possible that the insignificant differences in HR between the lower risk ratings are simply due to a lack of statistical power and that a larger study with more participants and/or risk rating locations would reveal significant differences.

The comparison of PDF and CDF curves in Fig. 9 demonstrates that the distributions of HRs within each Risk Rating group are similar, but with distinct averages. Calculations of skewness and kurtosis as well as the results of various tests of normality provide evidence that the samples come from normal populations, validating the use of the various statistical techniques employed in this study.

Table 6 shows that the probability of a cyclist incurring a HR in a particular HR zone varies with different levels of risk perception. In particular, there are notable differences in the probabilities of each HR zone when comparing RR1 to RR2 and RR2 to RR3. In general, as one moves up through the risk rating groups, the probability of incurring a HR in the lower zones-Very Light and Light-decreases, while the probability of incurring a HR in the higher zones- Moderate, Hard and Maximal-increases. There is little difference between the probabilities for RR3 and RR4. These results imply that HR based training aids and energy expenditure measurement devices may overestimate cyclists' training intensity and AEE even at relatively low levels of risk perception. If training takes place in a highly controlled environment (such as an indoor gym), this effect may not be relevant—unless the cyclist is very inexperienced. However, the possible confounding effect may be important for those who cycle for exercise on public roads.

4.3 Uncontrolled Experiment

4.3.1 Travel Diaries

Of the 38 relevant incidents recorded, 28 (approximately ¾) involved interaction with a motor vehicle, compared with 4 each for interactions with pedestrians and other cyclists. Almost all of the recorded incidents (and in particular those with the highest average risk ratings) suggest some fault on the part of a motor vehicle driver. Also, the experiment participants' average culpability rating across all incidents was very low at 1.72. This suggests that, not only are motor vehicles perceived as being the greatest source of risk but that drivers of motor vehicles are perceived as being almost exclusively to blame. This is in congruence with previous studies on risk perceptions of cyclists (Lawson et al., 2013b) .This perception may also be realistic: a study by Johnson et al. (2010) which considered video footage from the perspective of cyclists found that drivers were at fault in 87% of notable incidents.

It was observed from the diary entries that intersections are a high risk road element for cyclists. Over half of the recorded incidents occurred at an intersection. Incidents of type "Car turning right across cyclist at junction" had the highest frequency and highest risk rating of the study.

4.3.2 Road Element Type Survey

The road element with the highest average risk rating of 5.08 was "Busy road without bicycle lane" which was also the most frequently reported road element. In contrast, "Busy road with bicycle lane" and "Busy road with bus lane and bicycle lane" had respective risk ratings of 3.7 and 2.5. This demonstrates that the presence of cycling facilities such as bus lanes and bicycle lanes on busy roads can significantly reduce the insecurity felt by cyclists. Previous studies on road infrastructure and cyclist safety suggest that this perception is justified as on-road bike lanes have consistently positive safety effects for cyclists (Reynolds et al., 2009). The further reduction in average risk rating produced by presence of a bus lane as well as a bicycle lane may be due to the increased separation from car traffic. The lowest average risk rating of 1.08 attributed to “Off road cycle path” further emphasises that segregation from traffic considerably increases the security felt by cyclists in a mixed mode network. This corroborates the findings of a previous study which indicated that cyclists prefer separated routes (Winters and Teschke, 2010).

The road element with the second highest average risk rating of 5.04 was “Roundabout where the cyclist continues straight on” (without cycling facilities). Although evidence shows that roundabouts reduce motor vehicle collisions by 30-50% (Elvik, 2003), this result would suggest that they are detrimental to perceptions of safety among cyclists. This perception is consistent with Moller and Hels (2008) which found that cyclists perceive the situation in which they are circulating in a roundabout and a car is exiting the roundabout particularly dangerous. Moller and Hels (2008) also found that perceptions of risk among cyclists are significantly higher in roundabouts without a cycle facility. There is evidence that these perceptions are justified in a 2009 literature review which found that multi-lane roundabouts can significantly increase risk to cyclists unless a separated cycle track is included in the design (Reynolds et al., 2009).

4.4 Limitations of Study

The following limitations should be considered when interpreting the results of this study. The study group was composed entirely of young males living in Cork city. The homogeneity in the study group allowed the study to focus on this particular prominent user group and prevent differences between subjects from dominating the results. However, for this reason, it is not known if a similar link between risk rating and HR would be observed in a group of different physical or social characteristics. Future studies may remedy this by using a more diversified study group, given that in these studies we believe we have developed and validated a methodology which would make a larger study worthwhile. Another limitation lies in the possibility that risky activities tend to involve more exertion. If situations which were perceived as being higher in risk tended to occur during moments of greater exertion; the observed differences in HR between different risk rating groups could have been confounded by the effects of exertion. It might be that the use of other sensors, which might quantify external factors such as gradients, wind and speed would increase the ability of the method to discriminate between exertion levels and risk perceptions. As the results show, even without this additional quantification, HR and perceived risk are clearly associated. Although these limitations would need to be addressed for detailed quantification of the relationship between risk perceptions and HR, this study was successful in demonstrating that the link exists and developing a methodology which may be replicated in larger studies.

5 Conclusions

The present study has found evidence that the heart rates of cyclists while cycling in a mixed mode urban network are linked to their subjective risk perceptions. It has been demonstrated that situations which are perceived by cyclists to be high in risk are likely to elicit higher heart rate responses than situations which are perceived to be low in risk. The dependency is most significant when comparing the highest risk ratings to all others but may still exist when comparing lower risk ratings to one another. Changes in heart rate in response to perceptions of risk while cycling may also be accompanied by other physiological responses such as release of adrenaline but further research would be required in order to establish this. This study also examined the risk perceptions of cyclists in relation to both the road elements they encounter on their regular commute and any specific incidents which caused a notable reaction or change in risk perception over a one week period. Busy roads and roundabouts without cycling facilities were perceived as most dangerous while facilities which separated cyclists from traffic greatly reduced risk perceptions. Most recorded incidents involved motor vehicles and the low culpability ratings of the experiment participants suggest that drivers were perceived as being at fault.

This research raises concern over the viability of using heart rate to measure training intensity and energy expenditure, particularly during activities which are perceived as being significantly high in risk. It can be postulated that the confounding effects of risk perceptions on heart rate-based exercise management tools are likely to be greatest when cyclists are in regular interaction with car traffic. This research also indicates that an important step to be taken in improving the perceived safety experience of cyclists would be the introduction of more dedicated cycling facilities which protect cyclists from motor vehicle traffic, particularly on busy roads and at roundabouts. Finally, the results encourage efforts such as the Road Safety Authority's "Cyclists - We All Share The Road" campaign which is aimed primarily at educating drivers on their responsibility towards cyclists as vulnerable road users (RSA, 2013).

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Figures

Figure 1. The three course types: (a) Slalom course, (b) Corner course and (c) Gap Course

Figure 2. Route 1 (Ant-clockwise)

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Figure 4. Evolution of heart rate for subject, E.B., during Gap course.

Figure 5. Distribution of median heart rates for each course type and difficulty level(L1, L2, L3) in the fully controlled experiment.

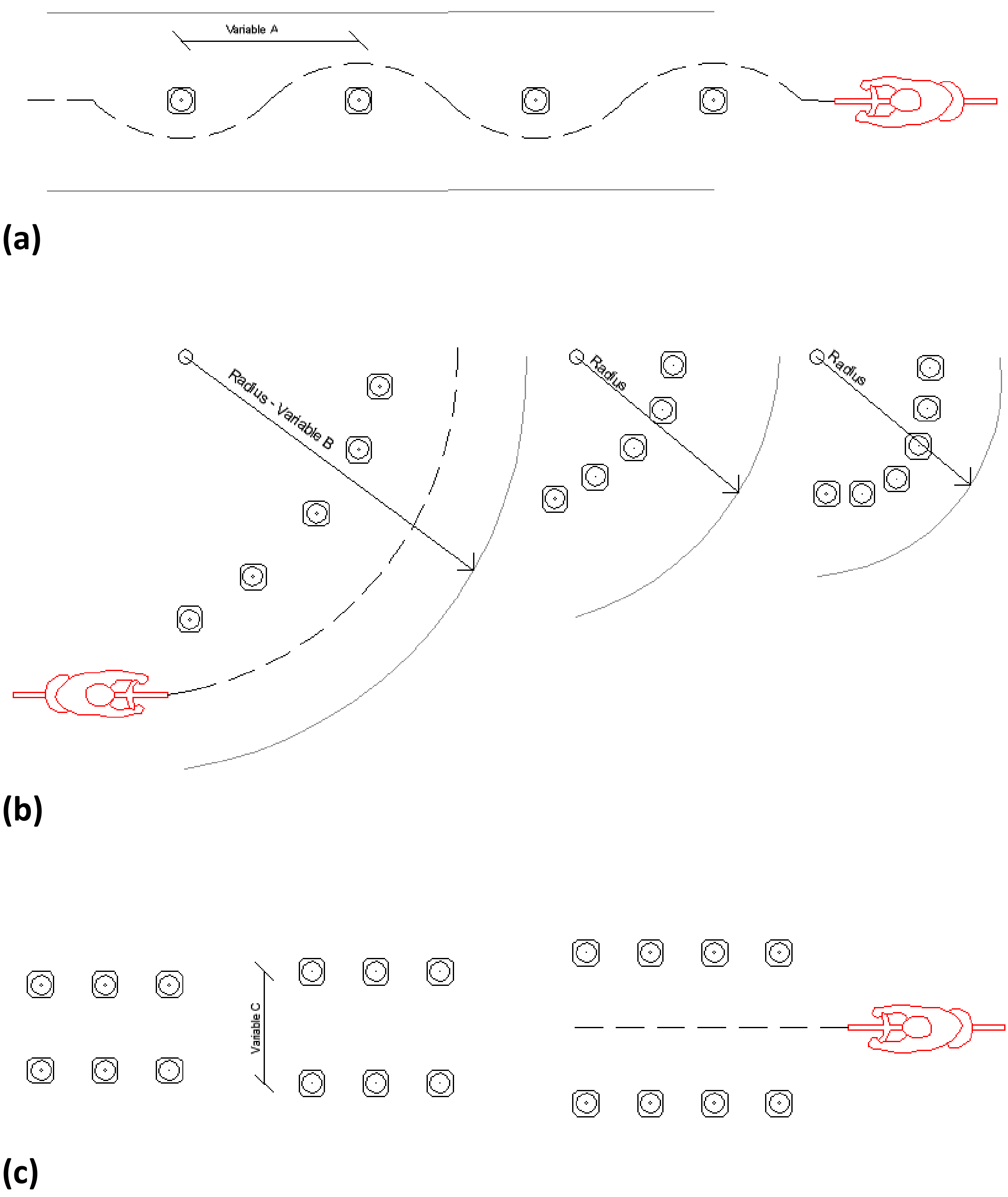
Figure 6. Frequency distribution of reported risk ratings.

Figure 7. Heart rate trend and risk ratings for subject O.K. while completing Route 1 of the Partially Controlled Experiment. Rating point identifiers are in squares and risk ratings are in circles.

Figure 8. Distribution of heart rates grouped by associated risk rating in the partially controlled experiment.

Figure 9. (a) Probability Density curves (PDF) and (b) Cumulative Density Curves (CDF) for the 4 risk rating categories.

Figure 10. Kernel density weighed curves, histograms and approximate normal density curves for (a) RR1, (b) RR2, (c) RR3 and (d) RR4.



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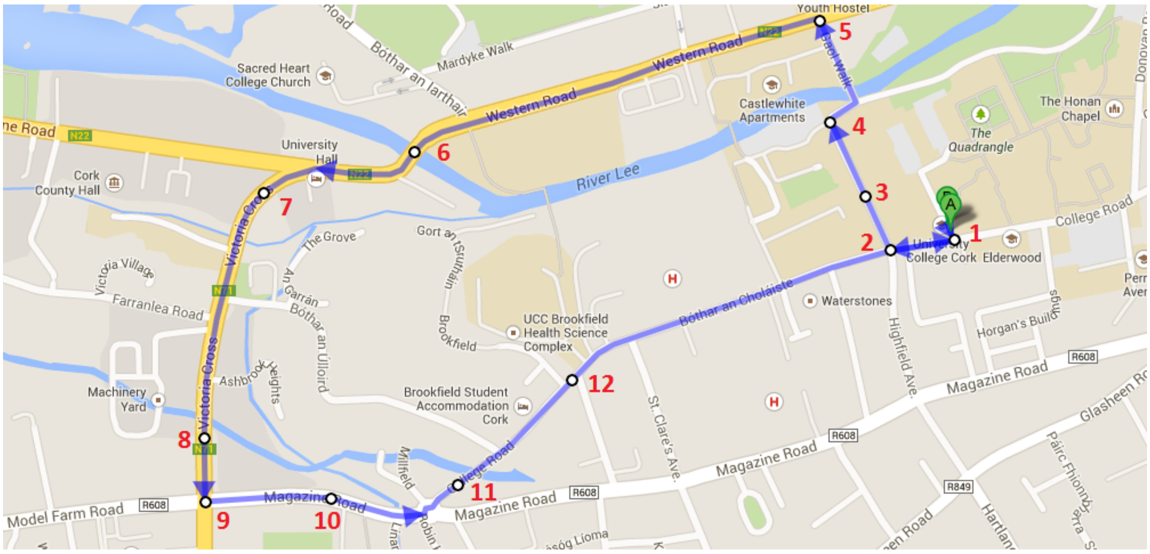

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(a) (b)

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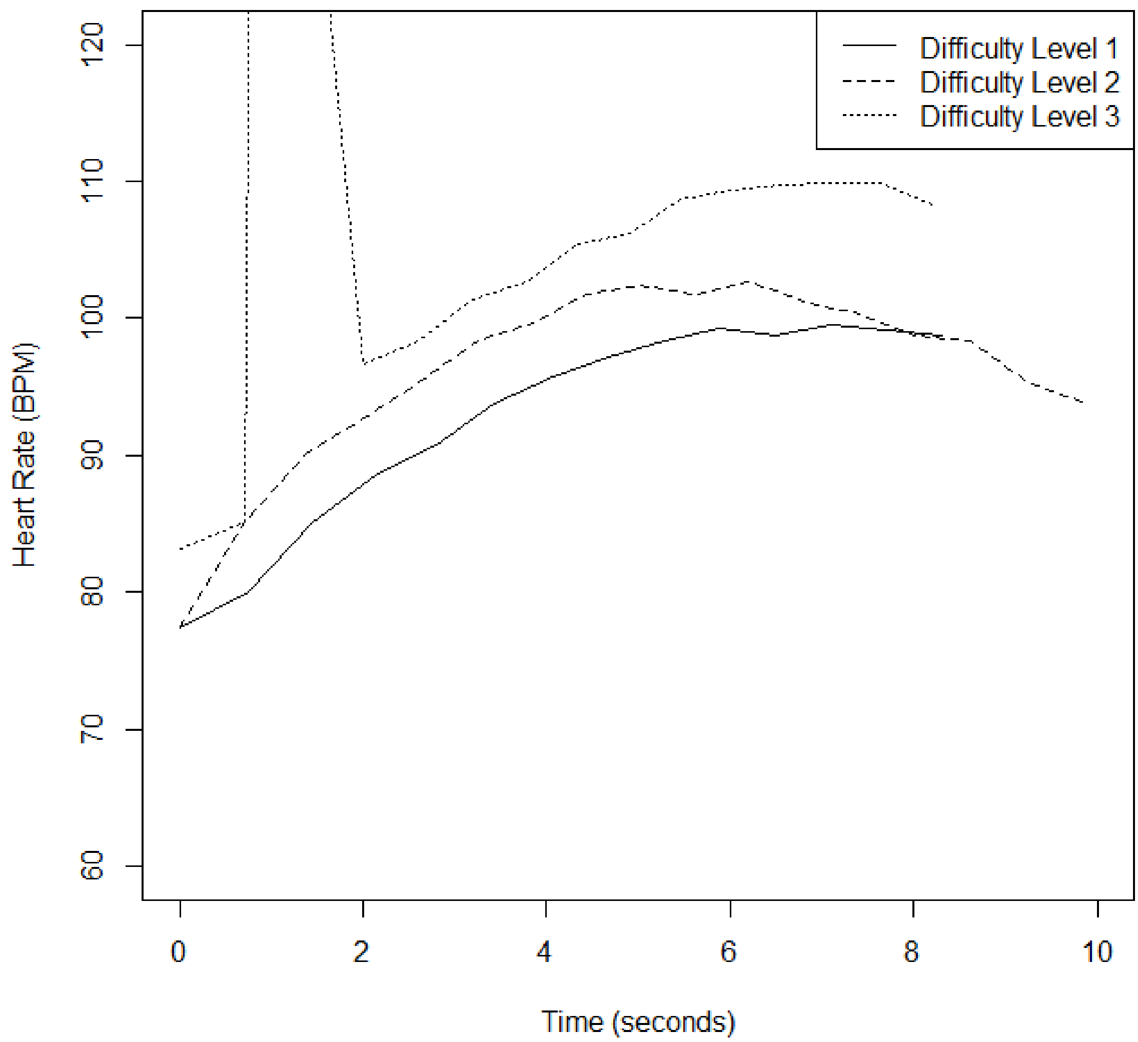

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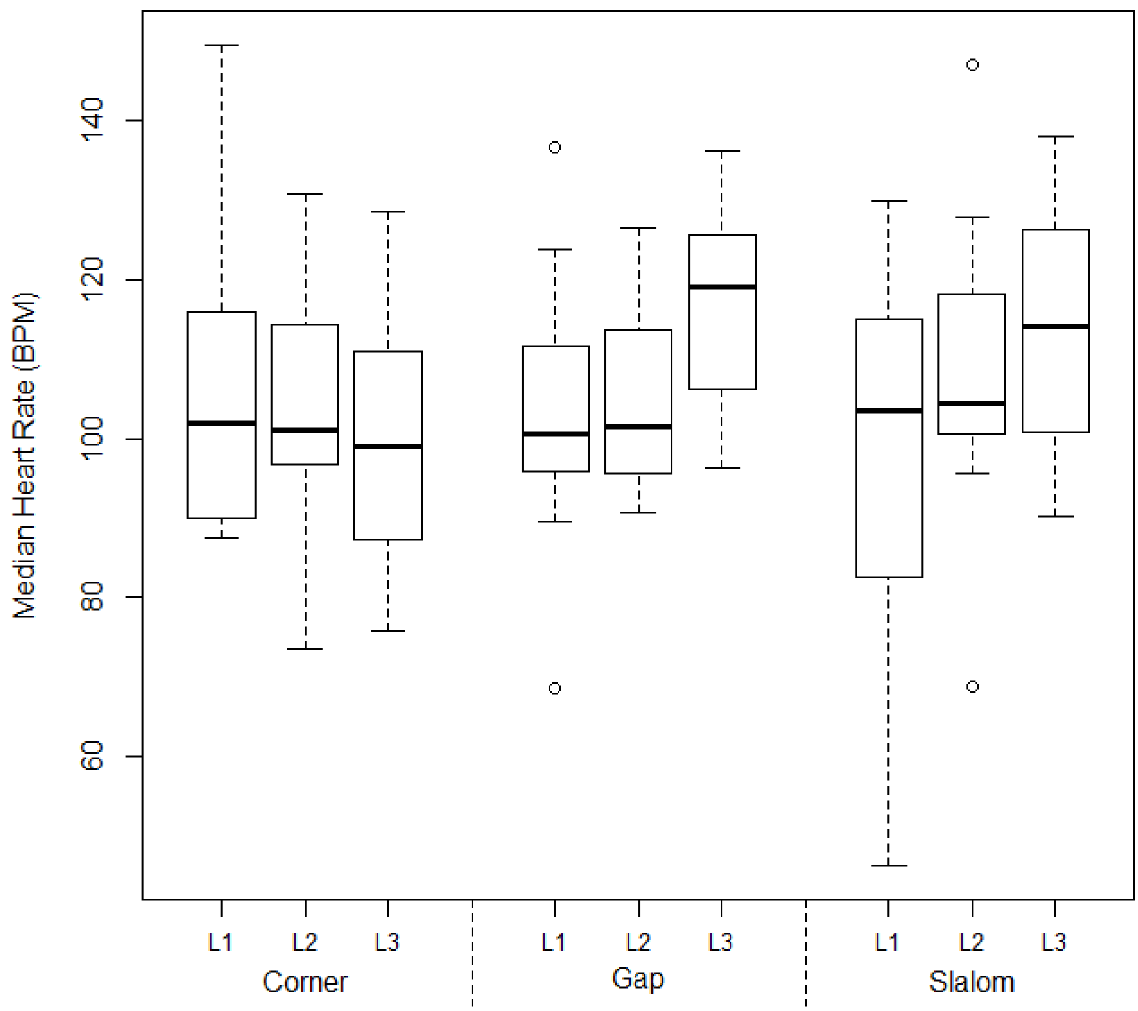

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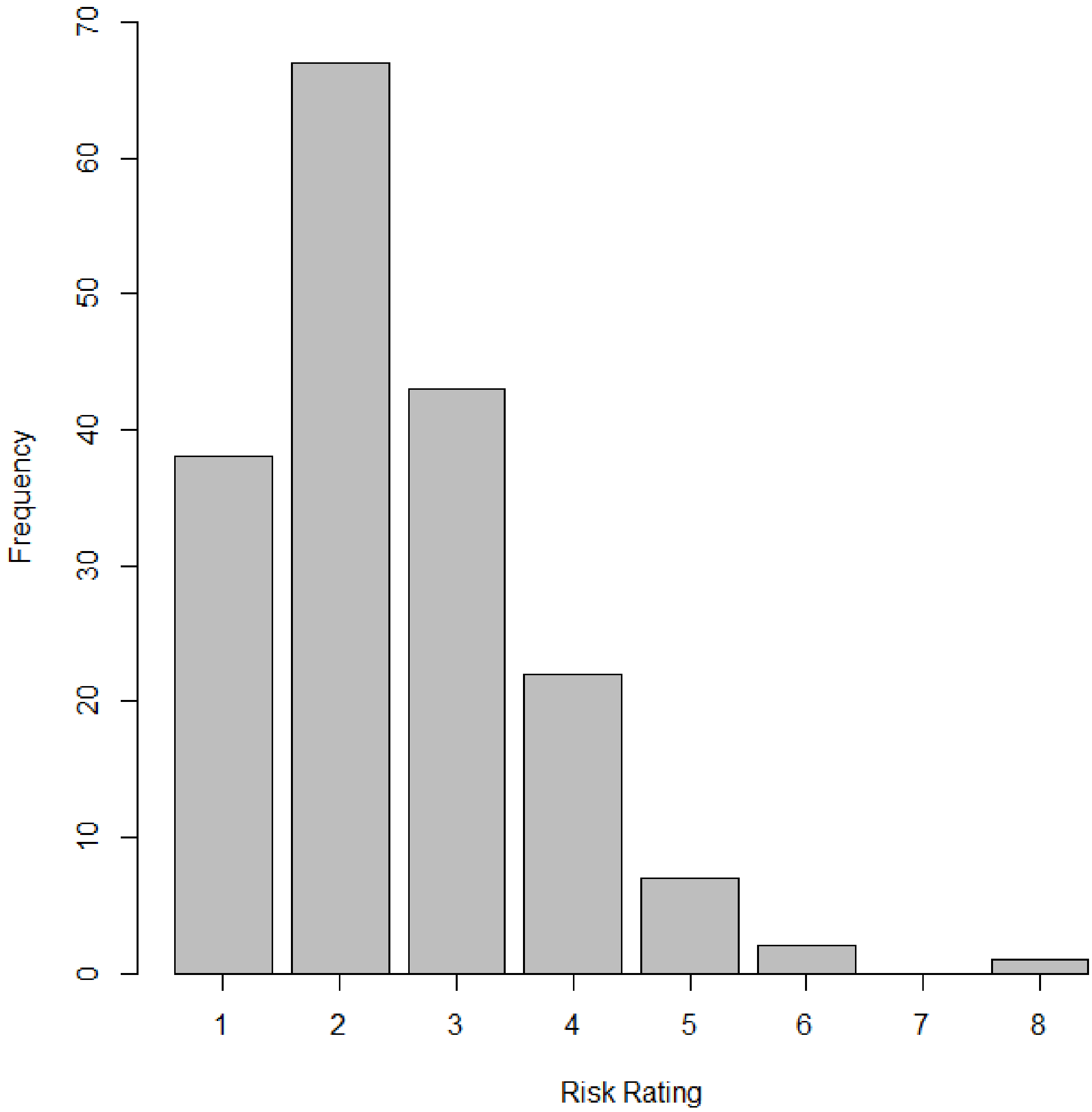

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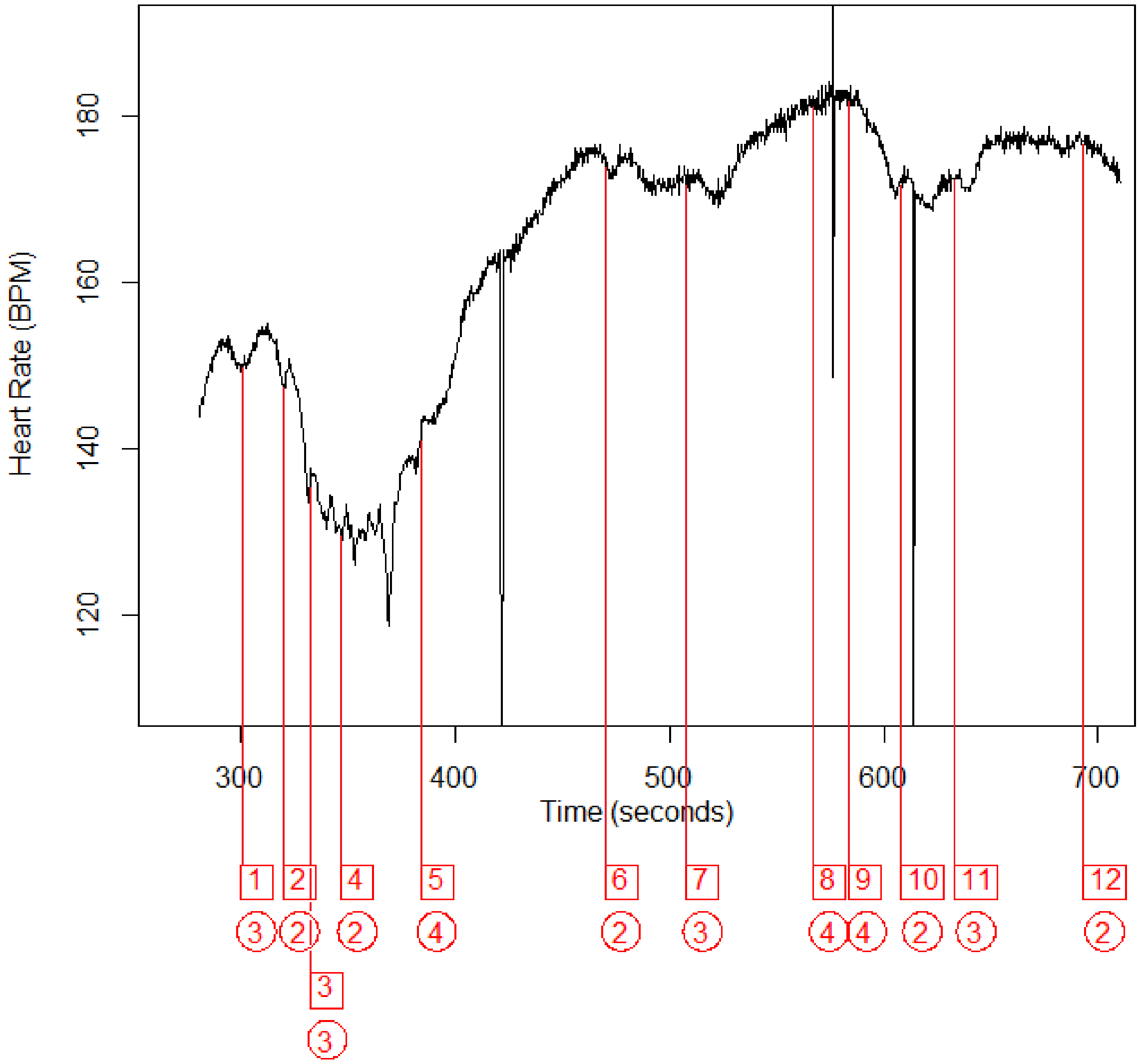

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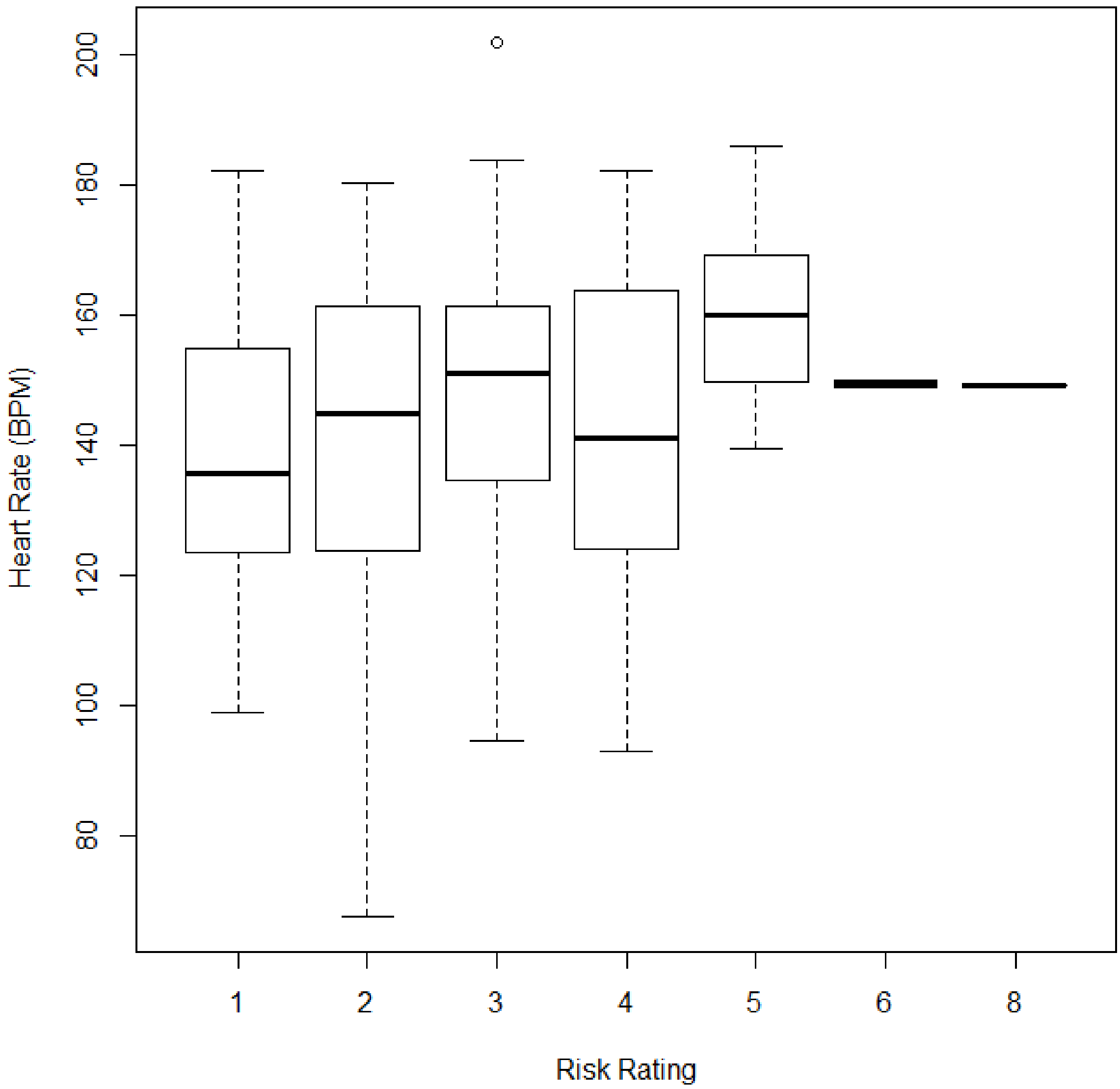

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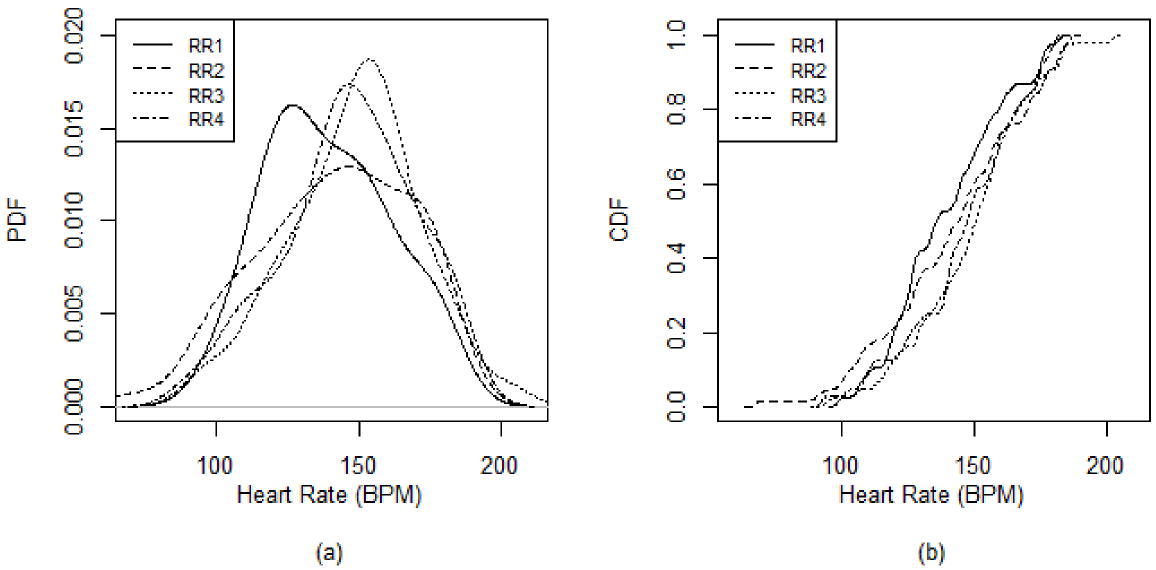

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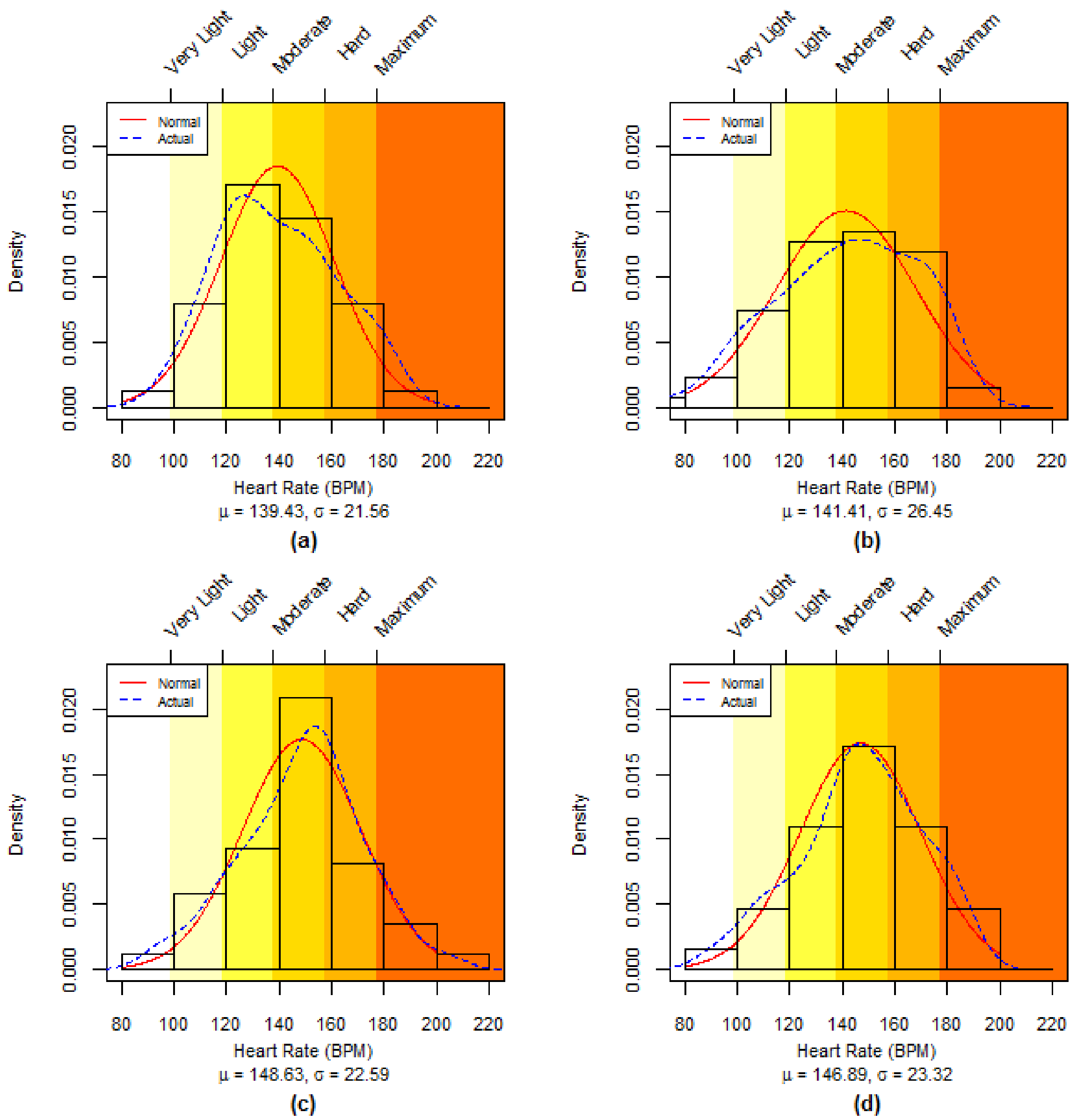

Fig. 10. Kernel density weighed curves, histograms and approximate normal density curves for (a) RR1, (b) RR2, (c) RR3 and (d) RR4. The approximate normal density curves were generated using the sample mean and sample variance. Heart rate zones are defined as recommended by Polar (2013).

Tables

Table 1

Roads encountered on routes in partially controlled experiment

Road	Class	Length (km)	AADT
College Road	Local Road	0.75	10251
Magazine Road	Regional Road	0.3	11595
Victoria Cross Road	National Secondary Road	0.45	19762
Carrigrohane Road	National Primary Road	0.17	26445
Western Road	National Primary Road	0.55	17840
Gaol Walk	Local Road	0.35	N/A[a]

[a] No traffic count data were available for Gaol Walk

Table 2 (a)

Risk rating scale for partially controlled and uncontrolled experiments

Perception	Very Little Risk				Moderate Risk					Risk of Severe Accident
Rating	1	2	3	4	5	6	7	8	9	10

Table 2 (b)

Culpability rating scale for diary incidents

Perception	Other completely at fault				Equally responsible					Self completely at fault
Rating	1	2	3	4	5	6	7	8	9	10

Table 3
Results of participant questionnaire

Participant	Height (m)	Weight (kg)	BMI (kg/m^2)	Physical Fitness Rating (1-10)	How often do you cycle?[a]	How long have you been cycling for? (years)
A.W.	1.85	79	23.08	6	3	16
B.R.	1.93	88	23.62	8	1	NA
C.G.	1.78	86	27.14	6	2	17
C.L.	1.91	86	23.57	10	1	NA
D.OD.	1.83	92.08	27.5	6	1	NA
E.B.	1.83	86	25.68	9	3	17
E.McN.	1.88	114.3	32.34	3	1	NA
M.P.	1.8	82	25.31	9	1	NA
O.K.	1.8	82.5	25.46	4	4	4
R.C.	1.8	75	23.15	5	2	12
R.McI.	1.8	73	22.53	5	2	1
S.C.	1.88	82.6	23.37	5	2	11
S.P.	1.78	80	25.25	7	1	NA

[a] Options were 1 (Never), 2 (A few days a week), 3 (5 days a week) or 4 (Every day)

Table 4

Student-Newman-Keuls Test Results

Risk Rating	Mean HR	Set
1	139.43	B
2	141.41	B
3	148.63	A:B
4	142.22	B
5	160.5	A

Table 5

Properties of the sample heart rate distributions for each Risk Rating category

Risk Rating	Mean	Variance	Skewness	Kurtosis
1	139.43	477.37	0.24	-0.84
2	141.41	710.25	-0.42	-0.51
3	148.63	522.35	-0.19	-0.06
4+	146.88	543.89	-0.33	-0.42

Table 6

Probabilities of each heart rate zone conditional on risk rating

	$HR_{Recovery}$	$HR_{Very\ Light}$	HR_{Light}	$HR_{Moderate}$	HR_{Hard}	$HR_{Maximal}$
C_1	0	$0.5HR_{max}$	$0.6HR_{max}$	$0.7HR_{max}$	$0.8HR_{max}$	$0.9HR_{max}$
C_2	$0.5HR_{max}$	$0.6HR_{max}$	$0.7HR_{max}$	$0.8HR_{max}$	$0.9HR_{max}$	∞
$P\{C_1< HR <C_2 \mid RR1\}$	0.03	0.17	0.31	0.26	0.17	0.07
$P\{C_1< HR <C_2 \mid RR2\}$	0.08	0.14	0.21	0.25	0.22	0.1
$P\{C_1< HR <C_2 \mid RR3\}$	0.03	0.09	0.19	0.33	0.25	0.11
$P\{C_1< HR <C_2 \mid RR4\}$	0.03	0.1	0.2	0.32	0.23	0.11

Table 7

Summary of diary incidents

Incident Type	Frequency	Average Risk Rating	Average Culpability Rating
Car overtaking closely	5	6.8	2.2
Car pulled out in front of cyclist	5	5.0	2.2
Car turning right across cyclist at junction	5	8.0	1
Car parked/stopped in cycle lane	4	4.0	1
Incidents with pedestrians	4	4.3	3
Incidents with cyclists	4	4.8	1.5
Car door opened in front of cyclist	3	8.0	2
Car overtaking at speed	2	5.0	2
Car sideswiped cyclist	2	7.0	1
Poor road surface	2	4.0	1
Car turning left, cut across cyclist	1	6.0	1
Near head on collision	1	8.0	1

Table 8

Summary of road element type survey results

Road Element Type	Frequency	Average Risk Rating	SD of Participant Averages
Busy road without bicycle lane	76	5.08	2.24
Busy road with bicycle lane	13	3.7	2.25
Busy road with bus lane and bicycle lane	8	2.5	1.64
Roundabout, straight on	9	5.04	2.55
/with cycling facilities	0	-	NA
Intersection, NO traffic signals, straight	29	4.48	1.91
/with cycling facilities	0	-	NA
Intersection, traffic signals, right turn	14	4.3	2.32
/with cycling facilities	6	3.9	1.14
Intersection, NO traffic signals, right turn	18	4.02	2.35
/with cycling facilities	0	-	NA
Roundabout right, turn	1	4	NA
/with cycling facilities	0	-	NA
Roundabout, left turn	6	3.5	2.35
/with cycling facilities	1	2	NA
Intersection, traffic signals, straight	32	3.36	1.78
/with cycling facilities	2	3.5	NA
Intersection, traffic signals, left turn	13	3.33	1.87
/with cycling facilities	2	4.5	0.71
Intersection, NO traffic signals, left turn	19	3.17	1.46
/with cycling facilities	0	-	NA
Residential street with parking	29	2.53	1.73
/with cycling facilities	0	-	NA
Residential street without parking	20	1.89	0.93
/with cycling facilities	0	-	NA
Mini-roundabout	4	1.75	0.5
/with cycling facilities	0	-	NA
Off road cycle path	8	1.06	0.14

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