Physiological Responses to Roller Coaster Rides:

A Pilot Study on the Differences between Virtual Reality and Real World Measures

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Abstract

Introduction: The aim of the study was to measure and analyse arousal of roller coaster passengers in both VR and real-world to make a comparison between these situations. To make arousal testable two approachesare introduced: separating the ride in contiguous phases vs. grouping data by roller coaster elements.

Study 1: Participants watched roller coasters in virtual reality while their EDA and HR was measured. A decrease of these measures from the first to the last phase was found. Only a weak association of roller coaster elements with specific arousal reactions was observed.

Study 2: With a small group of participants an amusement park was visited to ride real-world roller coasters. No phase-dependent change of arousal was found. However, some roller coaster elements were accompanied with specific changes in arousal. For all roller coasters continuous EDA and HR is reported.

Conclusion: Even though no direct comparison between VR and real-world was conducted our research implies that both conditions have different effects on real-time arousal. We conclude that VR roller coasters can not be seen as an equivalent alternative to real-world roller coasters.

Contents

Introduction

Those familiar with the Misattribution of Arousal Theory might have come across this classic example: someone steps on a roller coaster and after getting off again strangers seem much more attractive (Meston & Frohlich, 2003). But roller coasters have much more capacity for psychological research than that. They have the special feature of making the rider undergo physical strain comparable to car racing, space shuttle take-offs or aerobatic flight manoeuvres ("Orders of Magnitude (Acceleration)", n.d.). At the same time riders of roller coasters do not undergo the cognitive burden of keeping control over their vehicle, maintaining an overview of flight data or calculating good flight paths. Roller coasters therefore yield good preconditions to quantify emotional and force-induced arousal which influences the limit for mental workload of those working in high-force environments (Koglbauer, Kallus, Braunstingl, & Boucsein, 2011).

Despite this advantage of roller coasters for studying force-induced changes in psychophysiology little research has been conducted on them so far. And, of the existing research, many studies have been based on virtual reality (VR). Since results from VR have been reported as if they were true for real roller coasters the question arises whether roller coasters in VR actually have the same impact as riding one in the real world. To answer this question, a two-part study was conducted with the aim of comparing responses between these two situations. For the first study VR was employed, the second part was then conducted in an amusement park.

For our studies we measured reactions as arousal following being exposed to specific parts of a roller coaster. When talking about "arousal" we mean heightened physiological activity whereas when talking about "stress" it is indicated that the arousing experience is evaluated to be negative and vice versa for "excitement" (McManus, 1992). To measure arousal we employed variables relating to heart rate (HR) and electrodermal activity (EDA). In general, changes in HR can point to both parasympathetic as well as sympathetic nervous system activity (Ernst, 2017) and happen within a short time frame after exposure to the arousing stimulus (4-8 seconds; Baumgarten, Baldrighi, Vogel, & Thümler, 1980; Globisch, Hamm, Esteves, & Öhman, 1999). Besides HR, cardiovascular activity can also be expressed as measurements of heart rate variability (HRV). While HR is the (local) average of or current expected number of heart beats per minute, HRV expresses how much the temporal distance of single heart beats varies (for a review of HRV see Shaffer, McCraty, & Zerr, 2014). EDA is the collective term changes in skin conductance which occur when sweat glands are filled with sweat (Dawson, Schell, & Filion, 2016). A difference can be made between skin conductance level (SCL), the tonic component of EDA, and skin conductance response (SCR), the phasic responses of EDA (Braithwaite, Watson, Jones, & Rowe, 2015). Responses of EDA are approximated to happen three seconds after the event.

What are the physiological effects of roller coaster rides?

To know whether effects of real roller coasters differ from those in VR we first need to know which psychophysiological effects have been reported before. And even though most research on physiological reactions to roller coaster rides has come from the field of medicine, some relevant information about psychological effects can be inferred from their findings.

The most common way of describing effects in the papers discussed here is by separating the roller coaster ride into four phases: the “start” phase before the ride (e.g. five minutes), an anticipatory phase (in most cases the lift hill), the actual ride and some time after the ride. Therefore, in the following section we want to address the question during which phase arousal is the highest.

One option is that most arousal is perceived before the ride. For example, Rietveld and van Beest (2007) reported an increase of dyspnea, i.e. stress-related difficulty or inability to breath, for persons suffering from asthma before roller coaster rides with dyspnea comparable to baseline after the roller coaster ride. Interestingly, they also found that participants' HR did not increase immediately before the ride. The opposite, a spontaneous increase of HR and SCR, has been found by several other scholars (Hinkle, 2016; Kuschyk, Haghi, Borggrefe, Wolpert, & Brade, 2007; Pieles et al., 2017). One special case is a study by Baumgartner, Valko, Esslen, and Jäncke (2006) for which an increase of SCR amplitude sums was reported but no such effect for HR. Since the mentioned change in psychophysiological signals happens when the roller coaster moves up the lift hill, where no strong g-forces act on the riders, Kuschyk et al. (2007) argue that the response must be emotional. This theory can be confirmed by a study on water slides. Most of the participants reached their highest HR while waiting for their turn at the top of the stairs, thus without externally caused motion (Hokanson, Brauer, Hokanson, Eldridge, & Maginot, 2016). In the study at hand we should also see an increase of arousal before the ride. To allow a quantitative evaluation hereof we will follow the example of Baumgartner et al. (2006) and compare the average of the measurements on the lift hill to those of the rest of the ride.

A second opinion, on where to find the most arousal during roller coaster rides, is that this is the case during the actual ride, thus, between the first drop and the end brake. In their pioneering study Pringle, Macfarlane, and Cobbe (1989) reported an average HR_{max} of 154 bpm during this phase. This number has been confirmed by Kuschyk et al. (2007; 155 bpm) and by Pieles et al. (2017) who, across different roller coasters reported a range of average HR_{max} from 142 to 165 bpm, with a total average of 158 bpm. However, it should be mentioned that Pieles et al. (2017) measured heart rates of children at 13.3 ± 1.5 years of age. Since the only evidence against the maximum arousal falling in this time frame is the study by Yamaguchi, Kanemaru, Kanemori, Mizuno, and Yoshida (2003) where, as mentioned above, arousal was not measured continuously, it is also likely that arousal is the highest during the actual ride. Note that this is mutually exclusive to the above described lift hill effect.

This previous option is mutually exclusive to the third option: arousal is the highest after a roller coaster ride. An increase of arousal from before to after the ride has been reported in several studies for different physiological measures, for example for HR (Kuschyk et al., 2007; Pieles et al., 2017; Rietveld & van Beest, 2007) and blood pressure (Kuschyk et al., 2007; cf. Rietveld & van Beest, 2007 or SCR (Hinkle, 2016). However, as Yamaguchi et al. (2003) noted this increase not necessarily has to be linear. In their study on responses of salivary α-amylase concentration to roller coaster rides they found a linear increase of arousal when participants were scared. On the other hand, when participants reported to enjoy the ride a decrease of arousal during the ride and an increase above the initial level after the ride was found was found. Taking α-amylase as a marker for arousal, which like HR and SCR is directly influenced by sympathetic nervous system activity, and considering that the salivary system has been found to react within short time (Maruyama et al., 2012), it could be concluded that effects during the ride are weak. However, to sample saliva during the ride Yamaguchi et al. (2003) placed test stripes in the participants' mouths for the whole duration of the ride (i.e. three minutes) whereas for the other samples the stripes were only kept in the mouth for 30 seconds. Therefore the values reported during the ride were averages.

Why are real world and VR roller coasters differently arousing?

Up to this point it was only discussed which part of roller coasters are considered to be arousing in earlier research. However, the goal of this study is to compare arousal between VR and the real world. Therefore the question arises why these two situations are assumed to be different. To discuss this point factors to arousal are classified by a model proposed by Roscoe (1992). For his study on pilots flying complex manoeuvres he presumed that EDA and HR are objective measurements for workload. It is stated that overall workload is a combination of cognitive, emotional and physical workload.

For the part of cognitive workload one of the main tasks of the rider is to maintain a concept of one's position in space. At least that is the conclusion of a study by Baumgartner et al. (2006), who observed brain activity of person seeing VR roller coasters using LORETA and EEG. For those individuals increased activity was found over cortical areas associated with spatial presence, mental rotation and homeostatic functions during the ride. These cognitive processes are supported by well-oriented head movements and free body motion (Wade & Jones, 1997). While the cognitive processes can be assumed to be present for both real and VR roller coasters, the auxiliary functions are limited during real roller coaster rides. First, because passengers are restricted by safety belts around the hips or shoulders from freely moving their upper body, and second, because uneven tracks or quick changes in horizontal acceleration can make it difficult to stabilize one's head position. Therefore it can be hard for riders of real roller coasters to maintain a full concept of orientation and position in space, whereas riders of VR roller coasters who can move (almost) freely and are not affected by external forces, should have less trouble to maintain spatial presence.

Another task to cognition is to keep attention to the current situation (i.e. retain presence). Arousal of cortical areas associated with presence on the other hand has been found to increase arousal by (virtual) roller coasters (Beeli, Casutt, Baumgartner, & Jäncke, 2008). Especially in VR presence can easily be disturbed due to missing or inconsistent sensory input. One extreme example hereof is the lack of wind during the ride. Even though this might not seem to be a major issue on it's own, one needs to realize that often the only auditory input during on-ride videos of roller coaster rides is the sound of the wind. But not only the feeling of wind is missing, likewise one lacks the feeling of the shown weather (e.g. when watching a video shot on a rainy day in a warm room) and the physical forces pushing one around in the seat. Besides multimodal discrepancies, VR yields several lacks within modalities. For example VR glasses are restricted in the field of view they supply: while the shown image while looking straight is similar to human field of vision nothing can be seen when turning one's eyes sidewards in VR. To shift one's field of view one has to turn the head towards the direction one wants to watch. Furthermore, it is often observed that VR glasses' frame rate shortly drops after a head movement. Drops in frame rate again are related to loss of presence (Barfield & Hendrix, 1995), and might therefore implicitly cause people to rather infer peripheral information than to turn their heads. While discrepancies like the ones named here could be a reason for loss of presence and therefore less affection by VR roller coasters, to our best knowledge no research has been conducted on the relevance of complete sensory information in VR containing quickly changing environments.

Besides the anticipation factor discussed above both VR and real-world roller coasters deliver the emotional thrill of exceptional speed and height. Nevertheless it is hard to say in how far realism influences the emotional perception thereof. Especially for those suffering from fear of heights, the strong emotional response to the shown heights might result in a loss of presence in VR so individuals know they are safe (Owens & Beidel, 2015; Peperkorn, Diemer, & Mühlberger, 2015); other scholars however indicate that exposure to heights in VR has the same effect as in the real world (Emmelkamp, Bruynzeel, Drost, & van der Mast, 2001). Emotional reception of roller coaster rides might additionally be tinted by the definitiveness of the decision to take the ride: when taking a virtual roller coaster ride one can quit at any time by taking off the glasses, whereas one has to take the full ride when stepping on a roller coaster in the real world.

Opposite to what one might expect real roller coasters also have soothing factors to them. For one thing, on-ride videos used in VR often do not provide a preview of the roller coaster to be taken, but start with the passenger sitting in the car. Consequently, riders in VR are not prepared for eventual loops or other elements on the ride. Real world passengers on the other hand get to see the roller coaster before they make a decision to take it and have the time they stand in the queue to mentally prepare for the ride. For the other thing, real roller coasters are often taken in the presence of friends or at least a stranger that will respond to short glances to their side (Kissel, 1965). The presence of another individual can have soothing effects when facing dangers. In VR on the contrary one is seated next to a stranger who will not respond to one gazing their way.

While no clear answer can be given to whether VR or real world is more arousing in the realms of emotion and cognition, we can be sure that only real world roller coasters have an impact on physical state of the participant. That physical forces on roller coasters actually have an effect on participants physiology has been shown by Pieles et al. (2017). In their study they found that roller coasters' maximum speed correlated with HR_{max} and g-force with the time it took for the HR to recover to its level before the ride. This could cause on to jump to the conclusion that all differences in arousal between real and virtual roller coasters are due to physical forces. However, it needs to be considered that the presence of physical forces has an impact on emotional and cognitive factors as well. For example, as stated above, shaking of the head caused by sidewards-directed forces can inhibit one's ability to stabilize gaze and therefore make it harder to orientate. Or physical forces pressing one in the seat or throwing one in the air might increase one's feeling of presence and make possible risks more salient. Consequently, effects on arousal seen in close temporal proximity to the impact of physical forces can not be considered mere results of these forces.

Judging from the evidence above the question what the difference between VR and real-coasters is, might be answered with: During real roller coaster rides physical forces act on the passenger that elicit cognitive and emotional responses that are weaker in VR. What remains unclear is, how big the difference in response is. One way to answer to this is by directly comparing arousal in VR with that in the real world. To do so, we measured psychophysiological data under both condition. Where forces are low, arousal should be mainly caused by emotional and cognitive processes and therefore data collected in VR should closely resemble real-world data. Whereas, where forces are high, VR data should not be a good predictor for real-world data.

How can patterns in physiological arousal be quantified?

For analysing the real-time data a model was needed that can express the relation of several continuous variables (i.e. the physiological data) and discreet classes (i.e. the elements of the roller coaster), and that can quantify the relation. For this purpose we used a SVM, a machine learning algorithm which is trained to identify different classes after being trained on a part of the data (Marsland, 2015). This algorithm has been yielding good results in earlier research on classifying epochs of high stress from psychophysiological data (Cho et al., 2017).

A SVM functions by finding the spatial separation between two classes when they are represented in a vector space. To find this separator, first, the vector to the data points of both classes that are closest to each other is determined (i.e. the support vectors; see Figure 1a). The separator for the data is then set to run through the middle of the distance between the end points of the support vectors (Figure 1b). To find the best separator, margins are set parallelly to both sides of the separation vector (Figure 1c). The better the fit, the more space between the margins and the less data between the margins or on the wrong side of the vector. A class is then defined as the space on one side of the margin. Based on finding their position in the vector space and the previously defined classes the SVM can then make predictions for new data (Marsland, 2015).

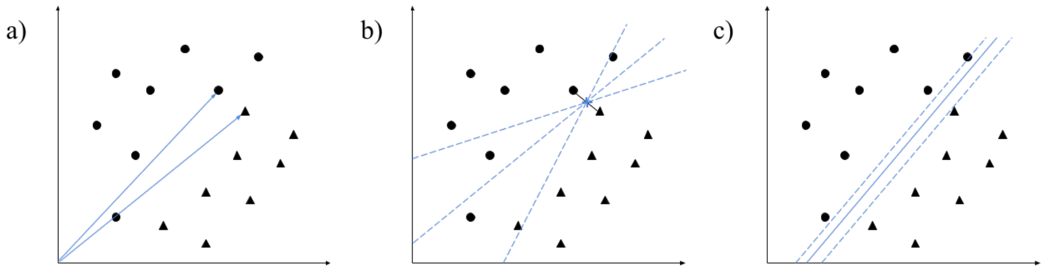

Figure 1. Conceptual functioning of a SVM. a) Finding the support vectors: vectors are drawn from the origin of the vector space towards the two closest data points of each class. b) Possible separation vectors: All considered options for a separation vector run through the middle of the connection vector between the data points identified in a). c) Setting the margins: The wellness of a separation vector is determined by applying parallel lines to both sides through the closest data point on each side; the more distance to the margins the better the separation vector.

A SVM works with linear separators. Since not all data can be fit by linear separators, predefined functions (i.e. kernels) can be used to transform data. Also, SVM can be modulated to compare more than two classes at once by comparing all available pairs of classes (one-versus-one) or by comparing each single class against all other classes (one-versus-all).

In our study we can used a SVM to analyse how closely VR data resembles real world data. After checking whether for each data set on its own a prediction can be made, we used the VR data as a training set to define the classes. Then we let the trained SVM classify the real-world data. Predictions for real-world data should be equally good when VR data is used for training as when real-world data is used for training, if they are not different. If, on the other hand, real-world effects are differing from those in VR the SVM should perform better when trained on real-world data.

In summary, we want to answer whether psychophysiological effects of VR roller coasters are similar to those in the real world by determining the phase with the highest arousal and by comparing the effect of single elements. We expect that arousal will either be the highest on the lift hill or during the actual ride. Additionally, we expect an increase of arousal from before to after the ride. In the direct comparison of arousal caused by roller coaster elements we take good classifications of real-world data by a VR-trained SVM as a sign that VR and real-world roller coasters closely resemble each other in terms of arousal caused by them.

Study 1

For the first study participants watched VR simulations of roller coasters. The measured data was first analysed as to whether it confirmed observations made in earlier studies. Second, it was tested whether the data gathered could be used to classify itself. If in that way internal predictability is proven data can be used as the training set for the second study.

Methods

Participants

Participants were recruited from the research pool of the University of Twente. The ethics committee of the Faculty of Behavioural, Management and Social Science at the University of Twente granted approval. The request herefor is registered under the number 180062.

Individuals self-reporting cybersickness[1], motion sickness or vertigo during roller coaster rides were strongly advised not to participate in the study. As it is the case for real-world roller coasters persons with heart diseases or existing pregnancy were not admitted to undergo the stress of riding a roller coaster; however, since no strong physical forces were to be applied, back injury was not handled as an exclusion criterion. All participants were compensated with 0.5 credit points which were necessary for course completion.

The final sample consisted of 42 students with an average age of 20.16 years (SD =

[1]Cybersickness is a condition similar to motion sickness experienced when watching VR. Results about the cause of cybersickness point to different directions but it is most commonly assumed that, similar to motion sickness, cybersickness is caused by the discrepancy between the motion perceived visually and the steadiness of the body at the same time (Davis, Nesbitt, & Nalivaiko, 2015). Symptoms include sweating and strong negative emotions (e.g. nervousness, fright), which have been found to affect physiological measures (see for example Kim, Kim, Kim, Ko, & Kim, 2005; Gavgani, Hodgson, & Nalivaiko, 2017, cf. Gavgani, Nesbitt, Blackmore, & Nalivaiko, 2017). Gavgani, Nesbitt, et al. (2017) also note that effects of cybersickness can last for several days.

1.65). The female to male ratio was 11:3. For one participant no further data was collected because their physiological data could not be captured correctly and they therefore discontinued participation.

Materials

Informed consent. Informed consent was given on printed forms including a summary of the procedure and a reminder that participation is voluntary (see Appendix A). A duplicate is given to the participant. In accordance with the General Data Protection Regulation (2016) consent is given in an active form (i.e. ticking "yes" or "no") and participants are provided with information how data will be stored and distributed.

Demographics and experience questionnaire. A second paper form was used to assess participants' demographics, their general tendency for motion sickness and vertigo, and how they perceived the VR (i.e. whether they felt sick and how scared and happy they felt; see Appendix B). To avoid discomfort and to prevent reactivity participants were offered to fold the paper twice after filling it in, so that the researcher will not immediately see the answers. However no participant used this option.

Tagging scheme. For analysis of data events had to be tagged in the used videos. Fourteen tags were used, therefor. One tag was set to each the beginning and the end of the video. The other tags were related to elements of the roller coaster: *Corkscrew*, *First drop*, *Helix*, *Hop*, *Loop*, *Roll* and *Tunnel*. These elements were perceived to give a broad enough description of distinguishable roller coaster elements without going to much into detail. For example, zero-g and heartline rolls which differ by the distance of the rotation axis to the passengers' point of gravity were included in the category *Roll*, whereas corkscrews which are rolls with a loop-like circumference were given a separate category. All tags and the criteria for positioning can be found in Table 1. The times that were marked in each video can be found in Appendix C.

Table 1
Tags and criteria used for marking events in the videos of the roller coaster rides

Tag	Description
Referential tags:	
Start	Start of the video. For reference only.
End	End of the video. For reference only.
Ride events:	
Brake	The car starts hanging in the brakes at top of *Baron 1898*'s lift hill.
Corkscrew	The car leaves the horizontal and starts ascending.
Drop	Small drop before the lift hill. The car leaves the horizontal.
End brake	The car hits the end brakes. Marks end of the ride.
First drop	The car starts moving down the descent after the lift hill. For *Baron 1898* this is the case when the brake is released, for the rest when the car leaves the horizontal.
Helix	The car leaves the straight and leans into the curve.
Hop	The highest point of a hop.
Immelmann	see "Corkscrew"
Lift hill	The car starts moving up the lift hill. Marks beginning of ride.
Loop	see "Corkscrew"
Roll	The car leans over or starts ascending into rolls.
Tunnel	The car enters a tunnel.

VR simulation. Four VR simulations were presented to the participant using an Oculus Go headset. The main part of this headset is a box (size: 190 x 105 x 115 mm; weight: 470 g) which contains a mobile device. Content is shown on a 5.5" display with a resolution of 2560 x 1440 px. To attach the device to the user's head a strap is laid around the back of their head. Since the Oculus Go is a stand-alone device, a controller is used by the participant for interaction (rather than remotely controlling it from a laptop; see Appendix D).

The VR videos shown were retrieved from YouTube (https://www.youtube.com/) and played in YouTube VR (Google LLC, 2018), an application devoted to playing content on VR glasses. Four VR videos were used in the study: three were on-ride videos of roller coasters, the other was a neutral stimulus to keep the participant still but engaged during the basement measurement. Additionally, showing the video had the advantage that participants could get used to the VR and the control of the glasses, or report cybersickness before being exposed to videos with high-motion content. The videos were arranged in playlists with the following order: (1) neutral video, (2) filler video (i.e. black screen; CandRfun, 2013), (3-5) roller coaster videos.

The neutral video shows four students guiding the viewer through the European Parliament in Strasbourg, France (Poolpio Immersive Content Agency, 2018). In about four minutes (03:57) participants get to see, among others, the plenary chamber, a short interview with former President of the European Parliament Martin Schulz and the Parliament's press room.

Since SVM classifications were to be based on roller coaster elements a well-considered selection of roller coasters had to be made. On the one hand, we wanted to include a broad range of elements. On the other hand, each element should preferably have several occurrences across all used roller coasters to create sufficient data for classification. An additional limiting factor was that for the second study the same or similar roller coasters had to be available to grant comparability. Consequently, the choice of the used roller coaster videos was made in several rounds. First, the videos found when searching for "roller coaster" on YouTube were narrowed to only include 360° videos. Then, videos were scanned for similarity with roller coasters in parks close to Enschede, Netherlands[2].

[2]Parks considered were Efteling (Kaatsheuvel, Netherlands), Walibi Holland (Biddinghuizen, Netherlands) and Phantasialand (Brühl, Germany).

For example, roller coasters that are constructed to use a lot of space resulting in longer straight passages are rather uncommon in Europe and are therefore not considered (for example see Six Flag Magic Mountain's *The Riddler's Revenge*[3]). Another criterion was how prototypical the featured elements were, meaning that they did not include uncommon thrill elements like top hats or induction accelerated roller coasters. However, an exception was made for Efteling's Baron 1898 (see below for more information); since it is located in one of the parks considered for the second study it was not excluded. Finally, videos that on watching yielded a bad quality - even though they had a good upload quality - were excluded. From the remaining videos three were chosen that together included various thrill elements. This process resulted in the following choice of roller coasters:

- *Mammut* located at Tripsdrill (Cleebron, Germany): A wooden coaster with simple elements. After the first drop the car passes three helix-airtime hill combinations. The ride ends after five consecutive, alternating banked turns. The total ride from entering the lift hill to the end brake lasts 143 seconds (02:23). The used video was uploaded by COASTERCREW Germany (2017). Due to the specific properties of wooden tracks the quality of the video is somewhat inferior to that of the other two videos. However, only one participant indicated that this cause feelings of sickness and a few others felt that this decreased their enjoyment of the ride.

- *Baron 1898* located at Efteling (Kaatsheuvel, Netherlands): A dive coaster with several inversions. After climbing the 40 meter lift hill the car is pushed to the edge of the first drop (87°) and then braked. The passengers look down the track facing a hole in the ground. After three seconds the car is released to drop. Driving through the hole the car immediately enters an Immelmann turn. Then one passes a zero-*g*-

[3]https://www.youtube.com/watch?v=-xNN-bJQ4vI

roll and a helix. Finally, the car drives over a bunny hop and though a banked turn. The ride from lift hill to end brake takes 54 seconds. The video uploaded by Efteling (2015) includes the waiting time of the car in the station. Matching the concept of the ride (i.e. mining) a song is sung to the passenger by the “Witte Wieven” (i.e. Dutch mythological spirits) who threaten the miners to sabotage their work.

- *Big Loop* located at Hansa Park (Sierksdorf, Germany): A steel coaster with a high density of inversions. After leaving the station the car drives through a small drop to gain enough velocity to drive through a 180° curve and on the lift hill. Immediately after the first drop one passes two loops. These are followed by a banked turn into two corkscrews. A helix leads the car back to the station. The ride from lift hill to end brake takes 99 seconds (01:39). The video used is uploaded by HeideParkResort (2017). *Big Loop* is a the same model as Efteling's *Python* with a few minor changes.

Physiology sensor. Physiological data was measured using a Shimmer3 GSR sensor with a sampling rate of 256 Hz. Data from the sensors is collected through a small box (6.5 cm x 3 cm x 1 cm), which was attached to the participant's lower arm. From there data was transmitted via Bluetooth to a laptop where it was recorded. On the laptop Consensys (Shimmer, 2017) was used to display real time data and to tag the start of the trials. Consensys automatically marks heart beats and derives heart rate and interbeat intervals. A full list of variables recorded for this study can be found in Appendix E.

Electrodermal activity (EDA) was measured with two electrodes attached to the palmar side of middle and ring fingers' proximal phalanges on the non-dominant hand. Initially, photoplethysmogram (PPG) was collected from the outside of the index finger of the same hand and also on the proximal phalanx. For 19 sessions the sensor had to replaced for an ear clip due to material breakage. This resulted in a decrease of detected heart beats from on average 95.18 % of the recording for measurements from the participants' fingers to on average 88.44 % for measurements from the earlobe.

Procedure

Participants were invited to one of the research cubicles at the University of Twente. After being asked whether they fall under any of the given restrictions and being informed about the procedure and purpose of the study, participants had the possibility to ask questions. When they indicated to have understood the given information participants signed the informed consent.

Subsequently, the Shimmer electrodes were attached and the quality of the data was controlled on the laptop. Before participants put on the VR glasses, they were shown how to use the controller. This knowledge was immediately practised by starting the neutral video. At the same moment as the participant started the video, the researcher started the recording of the transmitted data.

After the neutral video ended the participant was asked whether the glasses were sitting comfortable without moving and whether they were free from cybersickness. If no such problems were reported the participant was asked to continue to the next video, the roller coasters. The moment that the participant pressed the controller's trigger to forward was marked by the researcher as the start of the video.

At the end of the last roller coaster the recording of physiological data was stopped and the participant could take off the VR glasses and the sensor. Then they were asked to fill in the demographics and experience questionnaire. Before dismissal participants were again given the chance to ask questions and to share their experience of the experiment. The whole session took between 15 and 20 minutes.

Data analysis

Data was analysed using Python 3.7. The code can be accessed at https://github.com/luisewarnke/rollercoaster; relevant samples are given in Appendix F. The workflow of the analysis is shown in Figure 2. As shown in Figure 2 analysis happened in three phases which will be discussed in the following.

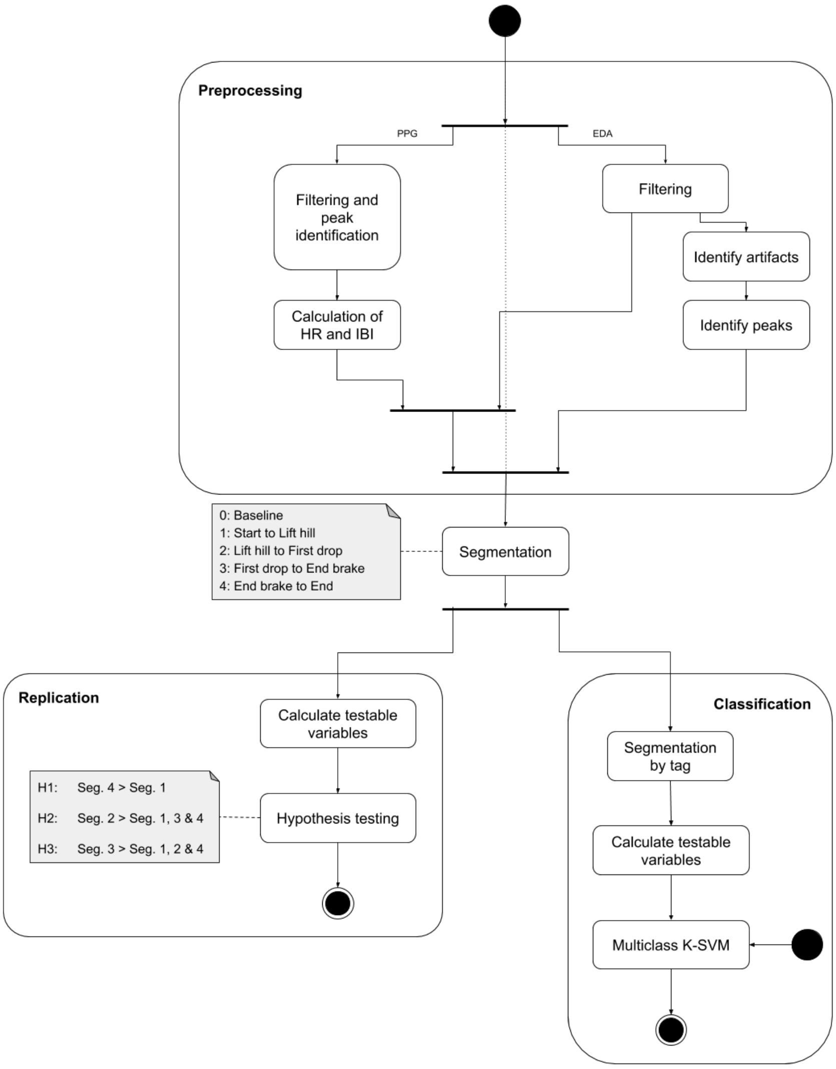

Figure 2. Activity diagram of the used analysis program. Data flows from the top to the bottom. *Replication* and *Classification* are executed independently. For *Classification*it is possible to use another, previously processed data set as training data.

Preprocessing. Preprocessing is handled by the program's `data_prep.py` script and its dependencies. For initial processing HR and EDA are treated separately.

HR and interbeat interval (IBI) were derived from PPG using the Python module HeartPy (2018; van Gent, Farah, Nes, & van Arem, 2018). Heart rate was appended to the data frame for all samples between two heartbeats while IBI is only given with the corresponding heartbeat (see Appendix G, Sample 1).

EDA data is preprocessed using EDA-Explorer (Taylor & Jaques, 2016; Taylor et al., 2015). This package applies a low-pass filter to the data, identifies artefacts and SCR peaks. Specifically, we applied a sixth order Butterworth filter with a cut-off of 1 Hz. For the artefact and peak detection scripts some changes were necessary, since they were written to be used with data sampled at 8 Hz (remember that our data was sampled at 256 Hz) and in accordance with Braithwaite et al. (2015) it was preferred to conserve the high sampling rate for researching changes that were expected to happen in a short time frame. Which lines were changed specifically can be found in Appendix G.

Replication. In a second step the assumptions made based on earlier research are tested. Herefor data is separated into five general segments: *Baseline*, *Start* to lift hill (S_1), *Lift Hill* to first drop (S_2), *Ride* form first drop to end brake (S_3), and from the end brake to the *End* (S_4). For each segment HR_{avg}, average HR_{max} of 10 second intervals, SCL and number of SCR peaks per minute are calculated (see Appendix G, Sample 2). Paired two-sided t-tests were employed to test the three assumptions made from earlier research: $S_4 > S_1$, $S_2 > \overline{S_1 \cup S_3 \cup S_4}$ and $S_3 > \overline{S_1 \cup S_2 \cup S_4}$. Tests were called from `exploration.test_segments()` using `ttest_rel()` from `scipy.stats`.

Classification. The third and last phase was the classification of the data. Herefor we first had to change the representation of the data to discreet classes with numeric variables describing them. Therefore data is separated into snippets from 1.5 seconds before to 1.5 seconds after each tag. For each segment the variables given in Table 2 are calculated using the simplified code given in the table (code is taken from `data_prep.prepare_tags()`). Note that all scores are relative. This is necessary for feeding them into the SVM: the algorithm thereof assigns weights to variables according to their absolute value; by rescaling variables to lay between 0 and 1 it is made sure that all variables will be assigned the same weight.

Table 2
Variables used for classification and pseudocode used for their generation.

Variable	Code	Description
Cardiovascular activity:		
HR_{avg}	`(data["HR"].mean()-baseline["HR_avg"])/(220-baseline["HR_avg"])`	Average heart rate
HR_{max}	`(data["HR"].max()-baseline["HR_avg"])/(220-baseline["HR_avg"])`	Maximum heart rate
$HR_{min-max}$	`(data["HR"].max()-data["HR"].min())/(lim_HR-baseline["HR_avg"])`	Difference between maximum and minimum HR
NN_{avg}	`data.IBI.mean()/(snip_len*1000)`	Average normal to normal interval

Variable	Code	Description
SDNN	`data.IBI.std()/(snip_len *1000)`	Standard deviation of NN intervals
SDSD	`[data.IBI[i]-data.IBI [i+1]].std()/(snip_len *1000)`	Standard deviation of difference between successive NN intervals
RMSSD	`[data.IBI[i]-data.IBI[ i+1]]**2.mean()**0.5/( snip_len*1000)`	Root mean squared of standard deviation of difference between successive NN intervals
pNN20	`len([data.IBI[i]-data. IBI[i+1]]>20)/len([data. IBI[i]-data.IBI[i+1]])`	Proportion of successive differences larger than 20 ms out of all NN intervals
pNN50	`len([data.IBI[i]-data. IBI[i+1]]>20)/len([data. IBI[i]-data.IBI[i+1]])`	Proportion of successive differences larger than 20 ms out of all NN intervals
Electrodermal activity:		
SCR_{avg}	`EDA_peaks.mean()/data. EDA.max()`	Average SCR
SCR_n	`(len(EDA_peaks)/snip_len )*60)`	Number of SCR peaks per minute

Note. Adapted from Cho et al. (2017).

The resulting data is then analysed using the SVM from the module scikit-learn. Seventy percent of the data set is used as a training set. For each of the standard kernels available (i.e. linear, polynomial, radial basis function (rbf) and sigmoid) the best fit was searched. To this end, the number of used variables and event tags was decreased iteratively, until the overall accuracy ($\frac{TP+TN}{TP+TN+FP+FN}$, where T: True, F: False, P: Positive and N: Negative) did not change considerably any more.

To identify variables that did not contribute to the classification the automatically assigned weights for each variable, which describe the used separation hyperplane, were used. The magnitude of the vector corresponding to each variable tells how much it contributes (Bitwise, 2012). Variables that yielded a magnitude below 0.2 were excluded.

The importance of the different events was analysed using the precision, recall (i.e.) and F_1-score (i.e. $2*\frac{precision*recall}{precision+recall}$). The *precision* tells the proportion of the data that was correctly classified as describing a certain event (i.e. True Positives (TP)) compared to all data that was classified to be describing this event, thus, also the data that actually not describe the event (i.e. False Positives; $\frac{TP}{TP+FP}$). The *recall* then describes the proportion of TP against data classified right, thus, TP and data that was correctly classified as not being the given event (i.e. False Negative; $\frac{TP}{TP+FN}$). The *F_1-score* describes the distribution of recall and precision. The better the SVM is able to classify the data the closer these three values get to 1. For decision of excluding elements from analysis the support (i.e. count of the event tag in test set) was used. Events of a support below 20 were excluded.

Design

The study used a within-subject time-series design. To prevent effects by stimulus order, a counterbalanced design was employed; for the three used stimuli this resulted in six conditions. Data was analysed as event-related activity.

Results

Participant experience

Eight participants (19.51 %) reported to experience motion sickness and four (9.76 %) to experience vertigo in general. Cybersickness, vertigo or motion sickness during the VR session was reported by eleven participants (26.83 %); four of whom as well reporting general motion sickness and three reporting general vertigo. In general the roller coasters made participants feel happy (much: 53.66 %; little: 43.90 %; not: 0 %), while ratings for scaredness were more diverse (much: 2.44 %; little: 46.34 %; not: 26.83 %; 24.39 % did not fill in that question).

Heart Rate

First exploration of the HR data showed that presentation order had no noticeable influence (see Figure H1). Strikingly, for almost half of the participants HR did not exceed 120 bpm. However, higher maximum HR was not associated with higher average baseline HR (see Figure H2). Additionally, when looking at the absolute maximum HR for each segement it was observed that the highest HR was reached during the baseline phase. However no such effect can be observed when HR_{max} per 10 seconds is used (see Figure 3).

Regarding the expectations from earlier research the following was found. Neither for the full dataset ($t(87)$ = -0.30; p = 0.76) nor for the separate videos (*Mammut:* $t(27)$ = 1.10; p = 0.28; *Baron 1898:* $t(28)$ = 0.88; p = 0.38; *Big Loop:* $t(30)$ = -2.99; p = 0.006) was an increase of HR after the ride as compared to before the ride found. For *Big Loop* HR even seems to decrease.

Furthermore, no support was found for arousal being the highest on the lift hill. The analysis rather indicates that HR on the lift hill is below the maximal HR for the

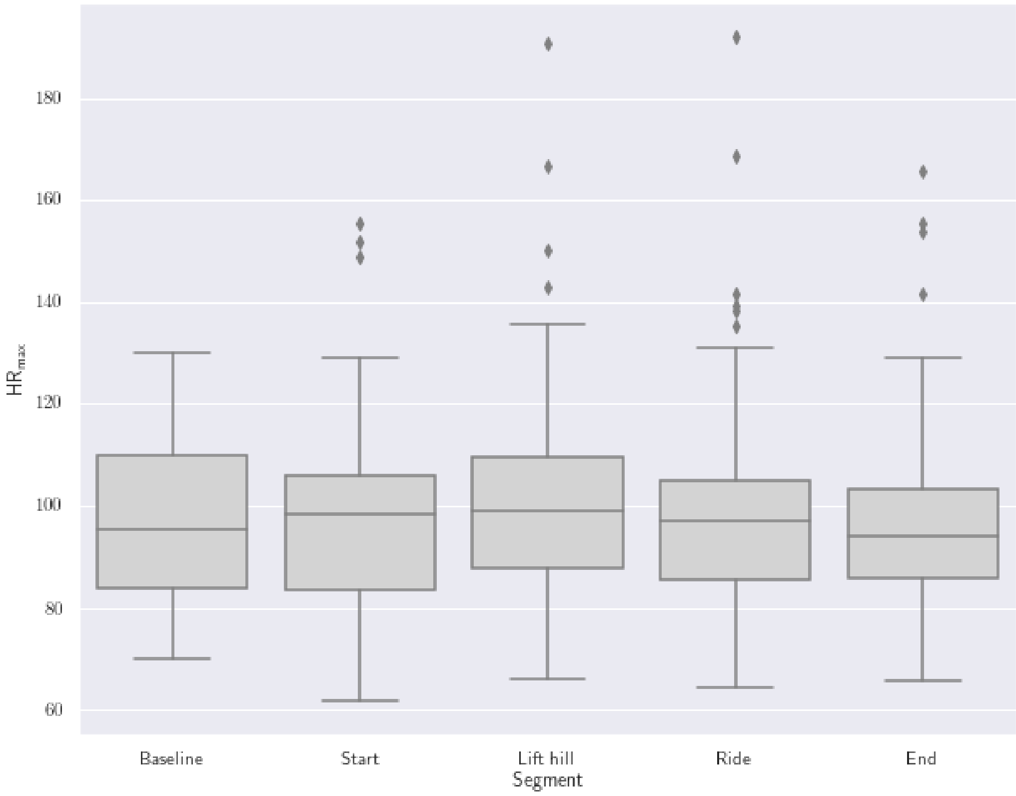

Figure 3. Box plot of time-normalized maximum heart rate for each phase of the VR study.

other segments ($t(90)$ = -2.93; p = 0.004; *Mammut:* $t(29)$ = -2.52; p = 0.02; *Baron 1898:* $t(29)$ = -2.25; p = 0.03; *Big Loop:* $t(30)$ = -0.40; p = 0.69).

Likewise, HR is lower than the maximum during the ride ($t(91)$ = -5.97; $p < 0.001$; *Mammut:* $t(30)$ = -3.45; p = 0.002; *Baron 1898:* $t(29)$ = -3.07; p = 0.005; *Big Loop:* $t(30)$ = -3.99; $p < 0.001$), contradicting the expectation that HR would be at its maximum during the ride. However, for both observations individual differences can be observed with only a few participants showing large changes throughout the experiment while most are seemingly unaffected (see Figure H3).

EDA

When looking at the number of SCR per minute a flooring effect becomes apparent Figure 6. Though this effect is more pronounced for conditions one, four and five, scores for all conditions stretch towards zero Figure H4. Additionally, it can be observed that for condition two the data measured during the baseline phase is lower than the rest of the session. Apart from that there seem to be no differences between the conditions.

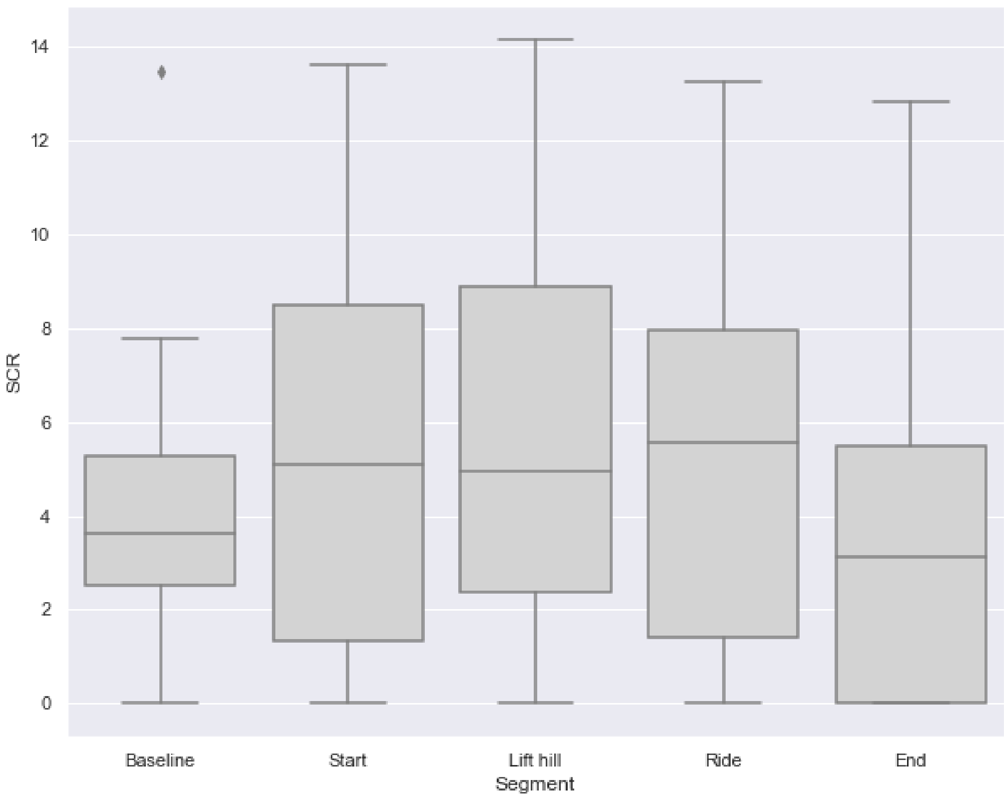

Figure 4. Box plot of number of SCR per minute for each phase of the VR study.

In contrast to the results reported for HR a difference was found between the start and the end. However, contrary to the expectation, number of SCRs decreased ($t(91) = -5.66$; $p < 0.001$). While this effect is pronounced for the aggregated scores, it is less distinct for the single rides (*Mammut:* $t(30) = -4.51$; $p < 0.001$; *Baron 1898:* $t(29) =$

-2.82; $p = 0.008$; *Big Loop:* $t(30) = -2.60$; $p = 0.01$).

Again, no sufficient support was found for the lift hill being the phase with most SCRs per minute ($t(91) = -3.50$; $p < 0.001$; *Mammut:* $t(30) = -1.89$; $p = 0.07$; *Baron 1898:* $t(29) = -2.59$; $p = 0.01$; *Big Loop:* $t(30) = -1.59$; $p = 0.12$). Nor for the ride being the most arousing part ($t(91) = -7.20$; $p < 0.001$; *Mammut:* $t(30) = -4.03$; $p < 0.001$; *Baron 1898:* $t(29) = -2.93$; $p = 0.007$; *Big Loop:* $t(30) = -5.55$; $p < 0.001$). That neither of the two moments has the highest score also becomes apparent when looking at the data split by participant (see Figure H5). No general trend can be observed; scores seem to be strongly individual.

Classification

The full linear model of all variables and event tags had an accuracy of 19.78 %. The same accuracy was found for the rbf and sigmoid kernel; for the polynomial kernel the accuracy was 19.42 %. However, this difference vanished after the first iteration. Therefore for the remainder of this section the output of the linear kernel is discussed.

The tag which was best classified was *Helix* (precision = 0.20; recall = 1.00; F_1 = 0.33). For all other tags the statistics returned zero. Therefore, decisions to remove tags from the model were in a first approach base on their representativeness of the sample (support is shown in Table 3).

Based on the variable magnitudes for the second iteration pNN20 and SCR_n were excluded. Also were *Brake*, *Immelmann* and *Roll* removed. This improved the accuracy by 3.70 % to a total of 23.48 %. Likewise increased the prediction accuracy for *Helix* (precision = 0.23; recall = 1.00; F_1 = 0.38). Again all other tags yielded zero for all statistics.

Table 3
Total accuracy, vector magnitude for each variable and event tag support per iteration for data gathered during VR study.

	Iteration 1	Iteration 2	Iteration 3
Accuracy	19.78 %	23.48 %	33.50 %
Variable			
HR_{avg}	2.7385	1.4297	1.2058
HR_{max}	2.4464	1.7328	1.6515
$HR_{min\text{-}max}$	2.6630	0.9215	0.8534
NN_{avg}	1.5646	0.9601	0.6362
SDNN	0.6154	0.2807	0.3183
SDSD	0.5055	0.1982	
RMSSD	0.0000		
pNN20	3.5888	3.6466	1.3850
pNN50	2.5721	1.499	0.7026
SCR_{avg}	5.5722	1.4993	1.8931
SCR_n	0.1850		
Event tag			
Lift hill	28	27	24
First drop	27	34	33
Drop	20	22	23
Brake	9		
Hop	51	42	38
Tunnel	22	19	
Helix	55	58	69
Loop	18	19	
Immelmann	13		
Corkscrew	21	26	19
Roll	14		

For the third iteration *Tunnel* and *Loop* were removed as well as SDSD. This resulted in an accuracy of 33.50 %, an increase by 10.02 %. Again the statistics for *Helix* increased (precision = 0.33; recall = 1.00; F_1 = 0.50), but no clear classification could be made for the other tags.

The last iteration consisted of removing *Corkscrew*. Nevertheless, this decreased the model accuracy to 31.89 %. Consequently, the tag combination used for the third iteration seemed to be the one that was best to be classified.

Building on the model from iteration three it was also tried whether a more parsimonious variable combination is possible. For this $HR_{\text{min-max}}$, NN_{avg}, SDNN and pNN50, which were yielding a magnitude below 1 were removed. This did not affect the prediction for the tag combination of iteration 3. Neither did it perform worse than a SVM using all variables in classifying all tags.

Discussion

We tested three hypotheses derived from earlier research: first, that arousal is higher after a roller coaster ride than before it, second, that the lift hill is more arousing than the rest of the ride, and, third, that the phase between lift hill and end brake is more arousing than the rest of the ride. In the study we carried out using VR neither could be confirmed. From data visualisation it rather seems that most participants are unaffected by the material. The decrease of SCR from the beginning of the session towards the end might indicate that participants, after initial arousal from, for example, anticipation get more relaxed during the ride.

Initially the SVM showed a low accuracy which could only reach mediocre values when removing rare events from the model. Changing the used kernel had no effect on the results. Data was classified with the same accuracy when only four variables were used for the model. Noticeably, the element that could be classified by the SVM is helices, which are long curves. Indeed, many participants reported that they were most affected by curves with regards to dizziness and sickness, even if they were not affected by the rest of the ride ("I didn't feel cybersickness as long as it was just going up and down."). On the one hand this could point towards a stronger effect of cognitively more challenging elements (which is described in more detail in the General Discussion). On the other hand, the measured arousal might be a mere response to cybersickness.

As noted above participants seemed to be highly aroused during the baseline phase. Even though this did not appear to be the case after time normalization the measured values were so high that we should discuss their possible origin here. One explanation herefor is the, for most participants, unused experience of VR. After all, only one participant reported to regularly use VR glasses. However, no decrease of decrease of arousal from the first to the last roller coaster, which would indicate that participants are getting used to the situation, was observed. An alternative explanation for the initial high arousal would be that, many participants experienced problems with the controller usage: instead of using the trigger to start the first video they pressed the “Back” button which is located close to the button that was used to unlock the glasses (see Appendix D). When this occurred the participant came to see a pop-up window with a prompt to confirm that they want to leave the video player. At this point participants usually asked whether they had to click “resume” whereupon they were informed that they confused the buttons and that they need to choose “resume” with the trigger. While most participants recovered from the mistake and now pressed the right button, others repeated the error and pressed “Back” again. If the latter was the case the stress experienced by the participant could be observed externally in form of strong sweating, unrest (e.g. fidgeting on the chair) and emotionalized comments (e.g. “I think I am just too stupid for this.”). Participants were calmed down (e.g. “You are not the first one who this happened to.”) and then step-by-step guided back to the right screen. Only in single cases was it necessary that the researcher had to take the glasses over and reset them to the right starting point. Whether participants managed to recover on their own or needed extra guidance it can be assumed that subjectively failing the given task caused feelings of frustration, confusion or embarrassment, which are then raising the measured parameters (Dehais, Causse, Vachon,

& Tremblay, 2012). Since no notes were taken on the occurrence of the above described error it was not possible to analyse data excluding the corresponding participants.

To avoid high stress by the way the VR glasses have to be controlled we want to advise for future research to use remotely controlled VR glasses, so that the researcher can start and stop the videos. Additionally, a longer video could be used for the baseline measurement to give the participant more time to get used to the unused circumstances of watching a VR video.

Study 2

The goal of the second study was to collect data from participants on real roller coasters. To answer whether this data differs from that collected in VR, the data collected for the second study should ultimately be classified using the data collected for the first study as the training set for the SVM.

Methods

Participants

Participants stemmed from a convenience sample, consisting of friends of the researcher. They actively declared interest in participation and content with not receiving a compensation. The following were handled as exclusion criteria: known heart disease, existing pregnancy and history of back problems.

Seven individuals participated in the study; five male and two female. Age ranged from 21 to 27 (M = 23.43; SD = 2.37). No participant reported to suffer from motion sickness or fear of heights. Only one participant had been to the visited theme park before. Remarkably, one participant mentioned in conversation that they had not been on a roller coaster before.

Material

Informed consent. Again, informed consent was given on printed forms by active confirmation. The form was the same as for the first study besides slight changes to the informative text (see Appendix I).

Demographics questionnaire. Likewise, was the demographics questionnaire an adapted version of that of the first study: the last three questions were removed and the question "Have you been at the *Efteling* before?" was added.

Roller coasters. The group visited the Dutch theme park *Efteling*. The roller coasters rode are described in the following:

- *Bobbaan:* A bobsled roller coaster. The ride starts by a small drop and a curve leading towards the lift hill. The first drop is followed by three alternating banked turns. Then, while passing a hill, the car is braked slightly. This is again followed by three alternating curves and another brake on a hill. Finally, the car passes another curve, a helix and then two more curves. The total ride duration from lift hill to end brake is 78 seconds.

- *Joris en de Draak:* A wooden coaster with two trains driving simultaneously to race each other. One train is called *Vuur* (Eng. fire), the other *Water*. We rode on *Water*, therefore only that ride will be described. The ride starts with a flat helix as a first drop. After the actual drop the train drives over three hops on a ascending track. This is followed by another helix, several curves with hops and a last helix. Seventy-five seconds (01:15) after the lift hill the car hits the end brakes whereupon the winner of the race is announced[4].

- *De Vliegende Hollander:* A water coaster which starts inside. The car is driving through a water-filled tunnel with several thrill elements: vases swinging over the passengers' heads, driving through fog and pouring rain - a waterfall which splits to leave the passengers dry - and finally a big ship seemingly running the passengers' little boat over. Accordingly, the car drives down a small drop, as it is being pulled under the ship. Then the car rises again and stops on the ascend. Passengers hear

[4]Our train won the race.

laughter and see the Jolly Roger above their heads. This marks the end of the first section of the ride which takes about 150 seconds (02:30).

Now, the car is pulled up the lift hill and drops outdoors. The car drives over a hop and through a horseshoe. This is shortly followed by the splashdown. From the lift hill to that moment the ride takes 41 seconds. This is the time frame considered for analysis. The remaining minute of the ride is the car driving through a lake back to the station. From leaving the station until the return there the ride takes 254 seconds (04:14).

- *Baron 1898:* See description above.
- *Python:* This roller coaster is nearly the same as *Big Loop* which is described above. The main difference is that before the drop into the double loop the car drives through a 180°curve. The ride lasts 78 seconds (01:18).
- *Vogel Rok:* An enclosed roller coaster which is, except short small-scale light effects, kept in the dark. The ride comprises a few helices and takes approximately 58 seconds.

Tagging scheme. The same tags as for Study 1 were used with one minor change for the *End brake* tag which for *De Vliegende Hollander* equals the splashdown. The temporal position of the tags was derived from the motion data collected with the Shimmer3 sensor (see Data Analysis).

Physiology sensor. EDA and PPG were measured using Empatica E4 wristbands. On the wristband the necessary sensors are build in a little box (25 g; 4.4 cm x 4.0 cm x 1.6 cm) which, like a watch, is located on the outside of the participant's arm. The device is controlled by one button; this can be used to switch the device on and off but also to tag times. As long as the device is turned on, data is collected and stored in the internal memory. To read the internal memory the program E4 manager (Empatica, 2018) is used; data can be viewed and downloaded via the online tool E4 connect. Data is output as directories containing one file for each measured variable. A full list of measured variables and the corresponding sampling rates is given in Appendix J.

Acceleration sensor. A Shimmer3 sensor without the EDA and PPG electrodes was used to measure the roller coaster motion and therefore to estimate the physical forces acting on the participants. The sensor was carried in the pocket of one participant and recorded the whole visit. The sensor was set to a sampling rate of 16 Hz and an accelerometer range of $\pm$ 16g. For more information on the Shimmer3 sensor see Study 1.

Procedure

The group of participants met in Enschede, The Netherlands, in the morning of the session. There the participants were briefed about the study and, after signing the informed consent, were handed the demographics questionnaire and the E4 wristband. At arrival in the park they switched on the wristbands and therefore started the recording.

No further instruction was given on the roller coasters that had to be ridden or in which order this had to happen. Rather, the coasters were chosen contemporaneously on basis of proximity and waiting times. As a result the roller coasters described above were taken in the given order. Due to delayed arrival, three participants did not take the roller coaster *Bobbaan*. Two participants did take *Vogel Rok* two times.

After approximately 5 hours the group left the park and with that ended the session. Wristbands were switched of and returned to the researcher.

Data analysis

Data was analysed as for Study 1 with the only difference that before applying the tags a temporal anchor had to be set. In preparation for this all data files were split into files for each roller coaster. These files started at the tags set on the E4 and ended one minute after the presumed duration of the corresponding ride (`data_prep.part_data()`).

For each of these files it was then assumed that the first ride related tag was where average motion in a 5 second interval was above 1 m/s^2 Appendix G, Sample 3). The resulting anchor was then used as the t_0 the times in the tagging files refer to. To grant a long enough time interval for the replication's "Start to Lift hill" phase the *Start* tag was set 20 seconds before the anchor.

First, events were classified using 69.9 % of the data from study 2 as a training set. Additionally, data from the second study was classified using the data from the first study as a training set. The resulting training set had 1.76 times the size of the test set (63.8 % of the total data set). The procedure for analysing the resulting statistics was the same as described for Study 1.

Design

As for the first study, the second study was designed as a time-series measurement and data was analysed as event-related activity. All participants took the roller coaster rides in the same order, meaning that there was only one condition.

Results

Graphs of all EDA and HR recorded during the roller coaster rides are shown in Appendix L.

Heart Rate

First exploration of HR_{max} showed that this data was not useable since almost all data points were set at 160 bpm. The scores reported in the following therefore are based on HR_{avg} (see Figure 5). For this measure it could be observed that scores were at a similar level for all roller coasters (see Figure K1). As for Study 1 responses seemed to be individually different rather than following any pattern (see Figure K2).

HR_{avg} seems to be at the same level before the ride as after it (H1: $t(23) = 0.29$; $p = 0.78$). This finding is not dependent on the roller coaster (see Table 4).

Neither does the data support that the HR on the lift hill is higher than during the rest of the session ($t(36) = -2.96$; $p = 0.004$); it is rather indicated that HR is lower for this phase. When looking into the results for the single roller coasters this only seems to be the case for *Vogel Rok*. For the other roller coasters HR is similar for the lift hill as for the rest of the ride.

Finally, it was tested whether the HR was higher during the ride than during the rest of the session. Again the opposite was found ($t(29) = -3.87$; $p = 0.006$). A lower HR during the ride was also found for *De Vliegende Hollander* and *Vogel Rok*. For the other roller coasters HR remained at the same level as for the other phases.

Table 4
Results of the paired t-tests on the average heart rate per roller coaster of the real-world study; p*-values are given in brackets.*

Roller coaster	End - Start	Lift hill - Rest	Ride - Rest
Bobbaan		$t(5) = -0.53$ (0.61)	$t(5) = -1.35$ (0.24)
Joris en de Draak		$t(6) = 0.18$ (0.86)	
De Vliegende Hollander	$t(5) = -0.93$ (0.39)	$t(5) = -1.41$ (0.22)	$t(5) = -2.99$ (0.03)
Baron 1898	$t(5) = 1.42$ (0.22)	$t(5) = -1.87$ (0.12)	$t(5) = -0.83$ (0.44)
Python	$t(5) = -0.26$ (0.80)	$t(5) = -1.60$ (0.17)	$t(5) = -1.57$ (0.18)
Vogel Rok	$t(5) = 0.08$ (0.94)	$t(5) = -4.09$ (0.009)	$t(5) = -2.69$ (0.04)

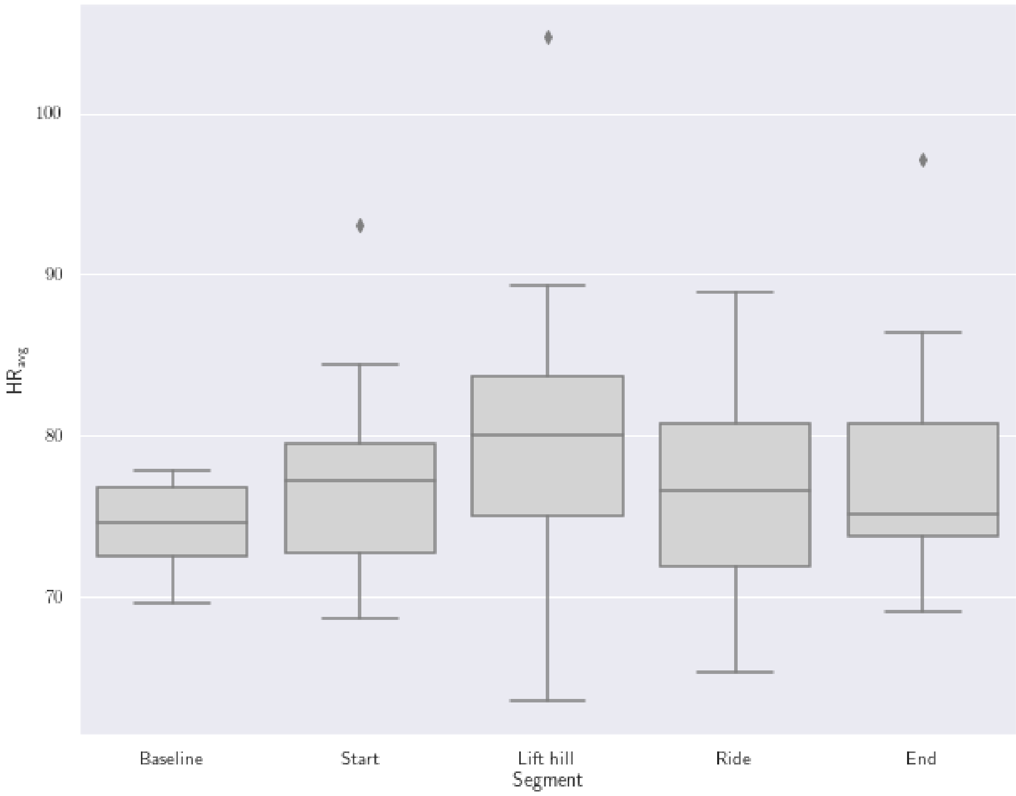

Figure 5. Box plot of average heart rate for each phase of the real-world study.

EDA

Again responses seemed to be rather individual than pointing to any general effect (see Figure K4)For the last three phases a flooring effect can be observed (see Figure 6). Additionally, an increase of SCR from the first to the last roller coaster can be observed (see Figure K3).

SCR is at a lower level after the ride than before ($t(23)$ = -2.16; p = 0.04). The same was found for *Baron 1898*. For the remaining roller coasters number of SCRs was similar before and after the ride (see Table 5).

Also, no more SCR were found during the lift hill than during the rest of the ride ($t(36)$ = -3.07; p = 0.004); again data indicates the arousal during the relevant is below the rest. This is also found for *De Vliegende Hollander* and *Baron 1898*. For the remainder, however, SCR seemed to be on the same level during the lift hill as for the rest.

For the full data set as well as for the single roller coasters arousal during the actual ride was not higher than during the rest of the video ($t(29)$ = -4.20; p = 0.002; Table 5, respectively); solely, for *Bobbaan* number of SCR for the ride phase is at the same level as for the other phases. Again it is indicated that SCR is actually lower.

Table 5
Results of the paired t-tests on the number of SCR per minute per roller coaster of the real-world study; p*-values are given in brackets.*

Roller coaster	End - Start	Lift hill - Rest	Ride - Rest
Bobbaan		$t(5)$ = -1.98 (0.10)	$t(5)$ = 0.39 (0.71)
Joris en de Draak		$t(6)$ = -1.27 (0.25)	
Vliegende Hollander	$t(5)$ = -1.18 (0.29)	$t(5)$ = -2.22 (0.08)	$t(5)$ = -2.11 (0.09)
Baron 1898	$t(5)$ = -2.50 (0.05)	$t(5)$ = -1.37 (0.22)	$t(5)$ = -2.38 (0.06)
Python	$t(5)$ = -0.37 (0.72)	$t(5)$ = -2.87 (0.04)	$t(5)$ = -3.87 (0.01)
Vogel Rok	$t(5)$ = -0.44 (0.68)	$t(5)$ = 0.14 (0.90)	$t(5)$ = -2.24 (0.08)

Classification

The SVM reached a accuracy of 32.68 % for the full data set and with a linear kernel. Accuracy was slightly higher for the rbf (34.64 %) and sigmoid (33.33 %) kernels. The polynomial kernel performed worse with an accuracy of 25.49 % (for all statistics see Table 6).

The tag *Hop* reached a precision of 72 %, a recall of 75 % and a F_1-score of 74 %. Also, did the tag *Helix* yield a certain degree of good classification (precision = 24 %; recall = 83 %; F_1 = 37 %). For the tag *Tunnel* which was also making up a significant portion of the data (support = 39) all prediction statistics returned zero. The same holds for the other tags.

For the second iteration the tags *Brake*, *Loop*, *Corkscrew* and *Roll*, which had a

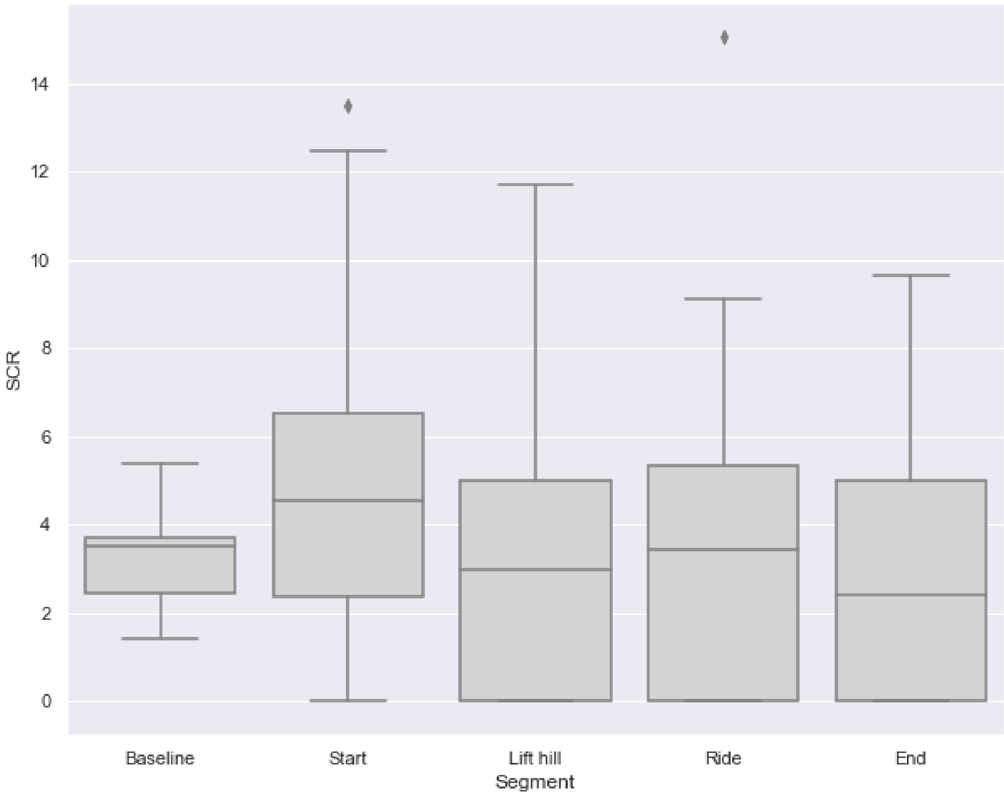

Figure 6. Box plot of number of SCR per minute for each phase of the real-world study.

support below 5 before, were excluded. Also were the variables SDNN, SDSD, RMSSD and SCR_n removed. This resulted in an increase of accuracy to 39.13 % for the linear kernel (rbf: 40.58 %; sigmoid: 39.86 %, poly: 28.26 %).

Prediction statistics for *Hop* decreased slightly from the first iteration (precision = 69 %; recall = 69 %; F_1 = 69 %). For *Helix* a even more severe decrease can be observed (precision = 21 %; recall = 8 %; F_1 = 11 %). Nevertheless, with the model of the second iteration *Tunnel* was predicted with a precision of 33 % (recall = 86 %; F_1 = 47 %).

After removing the tags *Lift hill* and *First drop* as well as the variable SCR_{avg} accuracy was 40.00 % for the linear, sigmoid and rbf model, and 30.43 % for the polynomial model. While predictions for *Hop* (precision = 68 %; recall = 77 %; F_1 = 72 %) and *Helix*

Table 6

Total accuracy, vector magnitude for each variable and event tag support per iteration for data gathered during the real-world study classified with real-world data as training set.

	Iteration 1	Iteration 2	Iteration 3
Accuracy	32.64 %	39.13 %	40.00 %
Variable			
HR_{avg}	2.0369	2.0189	1.4462
HR_{max}	2.4821	1.4698	1.0766
$HR_{min\text{-}max}$	2.2948	1.2376	0.9749
NN_{avg}	4.1971	4.1176	2.7596
SDNN	0.7207		
SDSD	0.8680		
RMSSD	0.0002		
pNN20	2.2558	2.4329	1.4063
pNN50	2.2558	2.4329	1.4063
SCR_{avg}	2.3744	0.7468	
SCR_n	0.1834		
Event tag			
Lift hill	9	7	
First drop	12	9	
Drop	19	18	15
Brake	4		
Hop	28	29	22
Tunnel	39	36	43
Helix	35	39	35
Loop	2		
Corkscrew	2		
Roll	3		

Note. Based on linear kernel.

(precision = 32 %; recall = 83 %; F_1 = 46 %) remained well, prediction statistics for *Tunnel* fell back to zero. Therefore no more variables were removed.

The final combination of variables yielded an accuracy of 33 % on all tags. The same accuracy was found for rbf kernel.

Combined Classification

When using the data from the first study as the training set accuracy was 25.79 % with the linear, 25.20 % with the rbf and 25.39 % with the sigmoid kernel (see Table 7 for all statistics). Accuracy with the polynomial kernel was slightly inferior at 24.21 %. However, the polynomial SVM outperformed the other three in making predictions for the single elements. The linear model was able to make predictions for two elements: *Lift hill* (precision = 27 %, recall = 8 %; F_1-score = 12 %) and *Helix* (precision = 26 %, recall = 99 %; F_1-score = 41 %). For the same elements the polynomial SVM yielded precision = 20 %, recall = 13 %; F_1-score = 16 % and precision = 26 %, recall = 86 %; F_1-score = 39 %, respectively. Furthermore, the polynomial SVM was able to identify *First drop* (precision = 50 %, recall = 3 %; F_1-score = 5 %), *Drop* (precision = 50 %, recall = 2 %; F_1-score = 4 %) and *Hop* (precision = 11 %, recall = 6 %; F_1-score = 8 %).

For the second iteration the variables SDNN, SDSD, RMSSD and SCR_n were removed. This resulted in an accuracy of 25.39 % for all kernels. Even though this was a small improvement for the rbf and polynomial kernel, the change cancelled out the predictions that could be made with all variables; the only element that was still predicted was *Helix* (precision = 25 %, recall = 100 %; F_1-score = 41 %).

To conserve the predictions of the different events the model was reset to the initial variable combination and instead the less frequent events were removed. Specifically, that were *Brake*, *Loop*, *Immelmann*, *Corkscrew* and *Roll*. With this accuracy for the linear kernel raised to 28.48 % (polynomial: 25.65 %; rbf: 27.83 %; sigmoid: 28.04 %). Again, the polynomial SVM performed better in classifying the different events. While the linear kernel's prediction statistics increased slightly (*Lift hill:* precision = 38 %, recall = 8 %; F_1-score = 13 %; *Helix:* precision = 28 %, recall = 99 %; F_1-score = 44 %), statistics for the polynomial kernel stayed at similar levels for the events *Lift hill* (precision = 14 %, recall = 10 %; F_1-score = 12 %), *First drop* (precision = 50 %, recall = 3 %; F_1-score = 5 %) and *Helix* (precision = 28 %, recall = 86 %; F_1-score = 43 %). Values slightly

Table 7

Total accuracy, vector magnitude for each variable and used event tag (x) per iteration as well as event tag support for data gathered during the real-world study classified with VR data as training set.

	Iteration 1	Iteration 2	Iteration 3	Iteration 4	
Accuracy	25.79 %	25.39 %	28.48 %	28.04 %	
Variable					
HR_{avg}	2.9069	2.8842	1.8742	1.7993	
HR_{max}	2.5614	2.5591	1.5024	1.4743	
$HR_{min\text{-}max}$	1.7981	1.9317	1.1152	1.0162	
NN_{avg}	1.1882	1.0464	0.7851	0.6894	
SDNN	0.6903		0.5322	0.5234	
SDSD	0.4447		0.2895	0.2596	
RMSSD	0.0000		0.0000		
pNN20	3.1338	3.2794	1.6533	1.6462	
pNN50	2.2170	2.7409	0.9290	0.9049	
SCR_{avg}	6.1945	4.8999	4.7051	3.2087	
SCR_n	0.2314	0.0957			
Event tag					Support
Lift hill	x	x	x	x	39
First drop	x	x	x	x	39
Drop	x	x	x	x	55
Brake	x	x			12
Hop	x	x	x	x	84
Tunnel	x	x	x	x	114
Helix	x	x	x	x	129
Loop	x	x			12
Immelmann	x	x			6
Corkscrew	x	x			12
Roll	x	x			6

Note. Based on linear kernel.

decreased for *Hop* (precision = 6 %, recall = 2 %; F_1-score = 3 %) and cancelled out for *Drop*.

For the fourth and last iteration the variables RMSSD and SCR_n, which in the iteration before had a magnitude below 0.1, were removed from the model. Accuracy decreased slightly (linear, rbf and sigmoid: 28.04 %; polynomial: 25.43 %). Also did the recall and F_1-score for *Helix* decrease by one percent and the precision of *First drop* by 17 % when using the polynomial kernel. The linear kernel was only able to predict *Helix* (precision = 28 %, recall = 100 %; F_1-score = 44 %) with this variable combination.

When the final variable combination is used for all events accuracy is 25.39 % for all kernels.

Discussion

As for Study 1 it was predicted that arousal after the ride would be higher than before it and that arousal on the lift hill is higher or, respectively, the arousal during the actual ride is higher than during the rest of the analysed section. Again, neither the first nor one of the latter two could be confirmed. However, unlike for Study 1 no decrease of arousal over the phases was observed.

Classifications made by the SVM reached mediocre accuracy which increased a good deal when restricting classification to frequent events. Furthermore was data fit better by a kernel SVM than by a linear SVM. Prediction accuracy for the final model with six variables was close to that of the full model.

Together these findings suggest that real roller coasters have local effects on arousal that differ between roller coaster elements. These effects, however, do not influence arousal for a prolonged time, so that average arousal in a specific phase of the ride is not increased.

Several problems occurred during the collection of the data, which due to the field situation, were not detected before analysis. First, as seen earlier, HR was only covered up to 160 bpm. This forced a slightly different approach for investigating the replication statements and therefore makes comparison to the first study difficult.

A second problem was that the used accelerometer lost its calibration and it was not possible to get absolute accelerations. Therefore it had to be chosen to set the anchors for tagging from acceleration magnitude rather than from directional movements. This could have caused inexact anchors for some of the roller coasters.

A less severe but still relevant observation is the increase of SCR from the first to the last roller coaster. This might have happened due to the warm weather on the given day and the resulting thermoregulatory sweating of the participants. Since for classification SCR is set as a relative value to the baseline, it seemingly becomes relevant from which moment of the day the training data is picked: if the training data is picked from the morning one element would cause a small number of SCR and therefore the SVM would not recognize the same element at the evening where it would cause more SCR. However, each classification is automatically rerun a number of times with switching, randomly chosen training sets. We therefore assume that the effect of the increasing SCR was cancelled out. However, future studies could avoid this problem by using times between rides as baseline data instead of only using the beginning of the measured data.

Aside from these points of critique the presented data shows that classification of real-time data is possible. The results could be improved by having all events represented equally often. Furthermore, measures should be taken to prevent motion of the sensors that cause it to malfunction.

General Discussion

The aim of our research was to measure and analyse the physiological effects of virtual as well as real roller coaster rides. For this purpose two different methods of analysis were used. The differences between virtual and real roller coasters in these analyses will be discussed in the following sections.

Analysis of ride phases

Neither for the real-world nor the VR study did we find the expected effects. Specifically, it was expected that arousal would increase from the start to the end of a roller coaster ride and that either the lift hill or the actual ride would be the most arousing part of a roller coaster.

These findings indicate that roller coasters do not have a prolonged effect on the passengers. However, it is possible that roller coasters cause short phases of arousal which are cancelled out when looking at the average arousal of longer phases.

That no effect was found strongly contradicts earlier research. Especially, that arousal increases from the beginning of the ride to the end of it has been reported univocally (Hinkle, 2016; Kuschyk et al., 2007; Pieles et al., 2017; Rietveld & van Beest, 2007). For the question whether the lift hill or the ride is most arousing results are mixed in earlier research and our studies were not able to introduce more evidence. This is especially striking, seen that the studies by Kuschyk et al. (2007) and Pringle et al. (1989), who found a clear increase of heart rate during the ride phase, are often cited on the effects of roller coasters. However, from these papers it did not become clear how data was analysed. In replicating the findings we chose for time-normalizing data and therefore used the average HR_{max} per minute and the number of SCR per minute, respectively. Since these measures might not be the same as those used in earlier studies results might not be comparable.

Remarkably, for both studies our data showed a strong spread between individuals. This could point towards individual differences that influence arousal caused by roller coasters. As noted earlier (Yamaguchi et al., 2003) observed for individuals who experience roller coasters as enjoyable a decrease of arousal during the ride was observed whereas for those who experience roller coasters as stressing an increase of arousal during the ride and then again an increase of arousal after the ride was observed. The found spread of individual scores combined with the use of t-tests which can only be used to compare two moments rather than the full progress, can have caused existing effects to be cancelled out. We therefore suggest to rather use analysis methods which take the whole course into account and to control for effects by subjective experience.

Classification by roller coaster element

Most noticeable, more roller coaster elements could be classified for the real-world study than for the VR study. Furthermore, the classification of the real-world data was more accurate even though less data was available. However, data from virtual roller coaster rides could be described using less variables than those of the real-world study.

The found pattern in classification could point to differently strong influences by the factors to arousal noted by Roscoe (1992): emotional, cognitive and physical. As mentioned above, the first part of the roller coaster ride containing the lift hill and first drop has been described causing an emotional response in earlier research since no forces or cognitive discrepancies are present at this moment (Kuschyk et al., 2007). Interestingly, neither for the VR nor the real-world study a classification could be made for these elements. However, a classification could be made when data from the VR study was used as a training set for the classification of real-world data. This indicates that emotional responses are similar in VR and the real world even though they might not be noticeable with a small sample size. As for cognitive arousal we claimed earlier that it can result from overcoming sensory discrepancies and the task of retaining spatial presence. In support for this is that for the VR study the SVM was able to discriminate helices, which induce a lateral turn and a roll of the visual field, while it was unable to discriminate hops, which occurred equally often but only resulted in a slight vertical shift. This indicates that the element which is more complex in its spatial changes causes a stronger response which can not stem from acting forces. For the real-world study, on the other hand, hops could be classified, pointing towards an effect of the physical forces acting here or at least a stronger effect on emotions and cognition when undergoing this element in the real world. This not only confirms findings by Hinkle (2016), who found the VR roller coasters have little effect on participants' arousal, but also those found by Pieles et al. (2017), that stronger g-forces are related to increases of arousal.

Even though the found pattern of arousal can be explained in this way, we must point to the fact that the exact timing of the tags could not be verified. While imprecision for the VR study should be low, no control was given in the real-world study. As explained above, the starting point of the tagging in the real world was taken from the acceleration data. However, accelerometers were not calibrated, meaning that one could not say whether acceleration was pointed towards one direction (e.g. upwards when starting to move up the lift hill) or rather uncoordinated (e.g. short shaking of the wrist). Consequently, the arousal samples that were used for classification might have stemmed from epochs that did not necessarily contain the given event and the found effects might actually be random rather than related to the events.

To improve the quality of results in future studies it is strongly advised to find a way to to get exact starting times for the roller coasters. This could for VR be established by using an event logging program on the glasses. For real-world measurements it needs to be made sure that an calibrated accelerometer is used. As a backup participants should get clear instructions to tag a specific moment (e.g. when the car starts moving). Nevertheless, to the best of our knowledge, the presented study was the first to further analyse the actual ride phase of roller coasters and the results indicate that more research should be directed to real-time effects of roller coasters.

Conclusion

As we aimed for, we were able to show differences and similarities of physiological arousal during real as compared to virtual roller coaster rides. Unlike earlier studies we did not only focus on larger segments of the ride but also looked into smaller parts thereof. In the end we were able to show that this kind of analysis might be fruitful.

Unfortunately, we were not able to directly compare data from both studies and, thus, we can not say whether the effects described here are actually due to a difference between roller coasters in VR and in the real world, or rather due to differences in the study designs. For one thing, the studies differed in the participant samples used: the second study used a way smaller sample with a significantly higher percentage of male participants. Also were none of the participants of the second study included in the VR study. As showed above, reactions might be individually different. Therefore, a comparison of data from different participants might not be valid. Likewise, the distribution of roller coaster elements differed between the studies, so that differences in accuracy might have been caused by elements that cause stronger reactions being represented more often in the real-world study. Moreover, the fact that in the combined classification, where more data was available, predictions for single elements was better, indicates that both studies would have needed more data, independent of the distribution.

Some suggestions can be made for future research. First, it should be controlled for systematic effects, that were not considered here. Besides increasing the roller coaster element sample and using the same participant sample for both studies, qualitative questions could be used to control for subjective experience of the participants. Specifically, it might be worthwhile to answer whether there is a systematic difference between those who experience roller coasters as stressful as compared to those who experience them as joyful. Second, a further step can to be taken to actually use real-time data for analysis. By separating data into snippets for each element we did ignore their actual place on the continuously measured data stream. Future research might for example look into the real-time data by training a machine to data snippets and then, instead of classifying predefined snippets, seek to tag elements in the full data by analysing time frame after time frame.

Especially with an eye on research using roller coasters towards an end other than entertainment, it can be made use of the controllability of the situation when using VR. By engaging elements for inducing forces by moving the passenger's chair or by reducing sensory discrepancies (e.g. by blowing wind into the passenger's face) more insights can be gained into the degree that specific factors influence arousal. This could then be used in pilot training. While it has already been shown that training in VR can help pilots decrease cognitive work during complex flight manoeuvrers (Koglbauer et al., 2011) it is unclear how this changes changes when transferring them to real planes. For example, sudden impact of forces during trained tasks could decrease wellness of performance. If this is true, training in roller coaster might help to get pilots used to working with forces acting upon them. This, in turn, could decrease the time that instructors need to be present in the plane with trainees.

Whether roller coasters find a more serious implementation or not, they remain an exceptional experience for riders. And even though it is not possible yet to resemble all aspects of the ride in VR, this technology can give a similar emotional experience to those who can not easily visit amusement parks.

Glossary of Roller Coaster Related Terms [5]

Airtime hill: Hill of parabolic shape causing the passenger to experience zero gravitation.

Bobsled coaster: A roller coaster that, instead of moving on rails, rolls on wheels down a pipe with several sharp, banked turns therefore resembling a bobsleigh ride (“Bobsled Roller Coaster”, 2018).

Bunny hop: Hills designed to cause experience of weightlessness. Unlike airtime hills, bunny hops cause short and abrupt upwards acceleration rather than letting the passenger float in to weightlessness.

Camelback: Long airtime hill.

Corkscrew: Roll with wide diameter.

Dive coaster: Roller coaster model with a first drop of about 90°. Often the car is braked at the top of the lift hill to left the passengers face the ground for a few seconds (“Dive Coaster”, n.d.).

First drop: First gravity accelerated motion of the cars. In most cases the first drop follows the lift hill but sometimes it is located right after the station to support motion towards the lift hill.

Heartline roll: Roll with small diameter so that the center line is at the height of passengers’ hearts. If the center line is placed correctly passengers experience negative gravitation and feel as if they are dragged off their seats.

Helix: Up- or downwards winding curve with wide diameter.

Immelmann turn: A half loop followed by a half roll. This combination makes it possible to include an up-side-down element when velocity is not high enough to include a full loop or to make a full turn on little space.

Inversion: Any thrill element where the car is turned upside-down (e.g. loops).

Lift hill: Section of the roller coaster where potential energy is created. In most cases this happens by pulling the cars to the top of a hill on a chain.

Splashdown: An element where water coasters hit the water to spray water (over the passengers) and to brake the ride. In many cases this is used instead of an mechanical end brake.

Zero-*g*-roll: The train twists up-side-down while moving on a slight hill. The combination of the twist and the hill causes zero gravitation.

[5] Adapted from “Roller Coaster Elements” (n.d.) and “Achterbahnelemente” (n.d.) unless other source is given.

References

Achterbahnelemente [Rollercoaster elements]. (n.d.). In *Wikipedia.* Retrieved on December 24, 2018, from https://de.wikipedia.org/w/index.php?title=Achterbahnelemente&oldid=181841519

Barfield, W., & Hendrix, C. (1995). The effect of update rate on the sense of presence within virtual environments. *Virtual Reality*, *1*(1), 3–15. doi: 10.1007/BF02009709

Baumgarten, R., Baldrighi, G., Vogel, H., & Thümler, R. (1980). Physiological response to hyper- and hypogravity during rollercoaster flight. *Aviation, space, and environmental medicine*, *51*(2), 145–154.

Baumgartner, T., Valko, L., Esslen, M., & Jäncke, L. (2006). Neural Correlate of Spatial Presence in an Arousing and Noninteractive Virtual Reality: An EEG and Psychophysiology Study. *CyberPsychology & Behavior*, *9*(1), 30–45. doi: 10.1089/cpb.2006.9.30

Beeli, G., Casutt, G., Baumgartner, T., & Jäncke, L. (2008). Modulating presence and impulsiveness by external stimulation of the brain. *Behavioral and Brain Functions*, *4*(1), 33–39. doi: 10.1186/1744-9081-4-33

Bitwise. (2012, October). *How does one interpret SVM feature weights?* [Blog post]. Retrieved from https://stats.stackexchange.com/questions/39243/how-does-one-interpret-svm-feature-weights

Bobsled roller coaster. (2018, December). In *Wikipedia.* Retrieved on June 25, 2019, from https://en.wikipedia.org/w/index.php?title=Bobsled_roller_coaster&oldid=898203435

Braithwaite, J. J., Watson, D. G., Jones, R., & Rowe, M. (2015). *A Guide for Analysing Electrodermal Activity (EDA) & Skin Conductance Responses (SCRs)* *for Psychological Experiments* (Tech. Rep.). Retrieved from University of Birmingham, Behavioural Brain Sciences Centre website: https://www.birmingham.ac.uk/Documents/college-les/psych/saal/guide-electrodermal-activity.pdf

CandRfun. (2013, November). *10 hours and 1 second of pure black screen!* [Video file]. Retrieved from https://youtu.be/XIMLoLxmTDw

Cho, D., Ham, J., Oh, J., Park, J., Kim, S., Lee, N.-K., & Lee, B. (2017). Detection of Stress Levels from Biosignals Measured in Virtual Reality Environments Using a Kernel-Based Extreme Learning Machine. *Sensors*, *17*(10). doi: 10.3390/s17102435

COASTERCREW Germany. (2017, October). *3D 4K 360° Roller Coaster - Mammut Gerstlauer Roller Coaster - VR180 Experience on-ride* [Video file]. Retrieved from https://www.youtube.com/watch?v=XgMjinox5LI

Davis, S., Nesbitt, K., & Nalivaiko, E. (2015). Comparing the onset of cybersickness using the Oculus Rift and two virtual roller coasters. In K. Pisan, K. Nesbitt, & K. Blackmore (Eds.), *11th Australasian Conference on Interactive Entertainment* (Vol. 167, pp. 3–14). Sydney, Australia: ACS.

Dawson, M. E., Schell, A. M., & Filion, D. L. (2016). The Electrodermal System. In J. T. Cacioppo, L. G. Tassinary, & G. G. Berntson (Eds.), *Handbook of Psychophysiology* (4th ed., pp. 217–243). doi: 10.1017/9781107415782.010

Dehais, F., Causse, M., Vachon, F., & Tremblay, S. (2012). Cognitive conflict in human–automation interactions: A psychophysiological study. *Applied Ergonomics*, *43*(3), 588–595. doi: 10.1016/j.apergo.2011.09.004

Dive Coaster. (n.d.). In *Wikipedia.* Retrieved on March 5, 2019, from https://en.wikipedia.org/w/index.php?title=Dive_Coaster&oldid=888483703

Efteling. (2015, October). *Baron 1898 in 360° - Efteling Onride* [Video file]. Retrieved from https://www.youtube.com/watch?v=HU6B237RaIo

Emmelkamp, P. M. G., Bruynzeel, M., Drost, L., & van der Mast, C. A. P. G. (2001). Virtual Reality Treatment in Acrophobia: A Comparison with Exposure in Vivo. *CyberPsychology & Behavior*, *4*(3), 335–339. doi: 10.1089/109493101300210222

Empatica. (2018). *E4 manager* [Software]. Retrieved from https://www.empatica.com/empatica-manager-download

Ernst, G. (2017). Heart-Rate Variability—More than Heart Beats? *Frontiers in Public Health*, *5*. doi: 10.3389/fpubh.2017.00240

Gavgani, A. M., Hodgson, D. M., & Nalivaiko, E. (2017). Effects of visual flow direction on signs and symptoms of cybersickness. *PLoS ONE*, *12*(8), e0182790. doi: 10.1371/journal.pone.0182790

Gavgani, A. M., Nesbitt, K. V., Blackmore, K. L., & Nalivaiko, E. (2017). Profiling subjective symptoms and autonomic changes associated with cybersickness. *Autonomic Neuroscience*, *203*, 41–50. doi: 10.1016/j.autneu.2016.12.004

Globisch, J., Hamm, A. O., Esteves, F., & Öhman, A. (1999). Fear appears fast: Temporal course of startle reflex potentiation in animal fearful subjects. *Psychophysiology*, *36*(1), 66–75. doi: 10.1017/S0048577299970634

Google LLC. (2018, November). *YouTube VR* [Software]. Retrieved from https://www.oculus.com/experiences/go/1458129140982015/

HeartPy [Python package]. (2018). Retrieved from https://github.com/paulvangentcom/heartrate_analysis_python

HeideParkResort. (2017, August). *Heide Park Resort Big Loop 360°* [Video file]. Retrieved from https://www.youtube.com/watch?v=gXsE9cDy3sQ

Hinkle, L. B. (2016). *Determination of emotional state through physiological measure-*

ment (Master thesis). Retrieved from https://digital.library.txstate.edu/bitstream/handle/10877/6411/HINKLE-THESIS-2016.pdf

Hokanson, E. S., Brauer, A. F. L., Hokanson, J. S., Eldridge, M. W., & Maginot, K. R. (2016). Heart rate and rhythm responses of healthy young adults to modern water slides. *International Journal of Cardiology*, *214*, 426–427. doi: 10.1016/j.ijcard.2016.03.192

Kim, Y. Y., Kim, H. J., Kim, E. N., Ko, H. D., & Kim, H. T. (2005). Characteristic changes in the physiological components of cybersickness. *Psychophysiology*, *42*(5), 616–625. doi: 10.1111/j.1469-8986.2005.00349.x

Kissel, S. (1965). Stress-reducing properties of social stimuli. *Journal of Personality and Social Psychology*, *2*(3), 378–384. doi: 10.1037/h0022223

Koglbauer, I., Kallus, K. W., Braunstingl, R., & Boucsein, W. (2011). Recovery Training in Simulator Improves Performance and Psychophysiological State of Pilots During Simulated and Real Visual Flight Rules Flight. *The International Journal of Aviation Psychology*, *21*(4), 307–324. doi: 10.1080/10508414.2011.606741

Kuschyk, J., Haghi, D., Borggrefe, M., Wolpert, C., & Brade, J. (2007). Cardiovascular Response to a Modern Roller Coaster Ride. *JAMA*, *298*(7), 739–741. doi: 10.1001/jama.298.7.739-c

Marsland, S. (2015). *Machine Learning: An Algorithmic Perspective.* Boca Raton: CRC Press.

Maruyama, Y., Kawano, A., Okamoto, S., Ando, T., Ishitobi, Y., Tanaka, Y., ... Akiyoshi, J. (2012). Differences in Salivary Alpha-Amylase and Cortisol Responsiveness following Exposure to Electrical Stimulation versus the Trier Social Stress Tests. *PLoS ONE*, *7*(7), e39375. doi: 10.1371/journal.pone.0039375

McManus, I. (1992). Stress, anxiety and psychosomatic disease. In *Psychology in Medicine* (pp. 193–208). doi: 10.1016/B978-0-7506-0496-3.50026-1

Meston, C. M., & Frohlich, P. F. (2003). Love at First Fright: Partner Salience Moderates Roller-Coaster-Induced Excitation Transfer. *Archives of Sexual Behavior*, *32*(6), 537–544. doi: 10.1023/A:1026037527455

Orders of magnitude (acceleration). (n.d.). In *Wikipedia.* Retrieved on February 9, 2019, from https://en.wikipedia.org/w/index.php?title=Orders_of_magnitude_(acceleration)&oldid=875694476

Owens, M. E., & Beidel, D. C. (2015). Can Virtual Reality Effectively Elicit Distress Associated with Social Anxiety Disorder? *Journal of Psychopathology and Behavioral Assessment*, *37*(2), 296–305. doi: 10.1007/s10862-014-9454-x

Peperkorn, H. M., Diemer, J., & Mühlberger, A. (2015). Temporal dynamics in the relation between presence and fear in virtual reality. *Computers in Human Behavior*, *48*, 542–547. doi: 10.1016/j.chb.2015.02.028

Pieles, G. E., Husk, V., Blackwell, T., Wilson, D., Collin, S. M., Williams, C. A., & Stuart, A. G. (2017). High g-Force Rollercoaster Rides Induce Sinus Tachycardia but No Cardiac Arrhythmias in Healthy Children. *Pediatric Cardiology*, *38*(1), 15–19. doi: 10.1007/s00246-016-1477-5

Poolpio Immersive Content Agency. (2018, January). *360° Tour of the European Parliament, Strasbourg* [Video file]. Retrieved from https://www.youtube.com/watch?v=DaVqd4h0ptM

Pringle, S. D., Macfarlane, P. W., & Cobbe, S. M. (1989). Response of heart rate to a roller coaster ride. *BMJ*, *299*(6715), 1575. doi: 10.1136/bmj.299.6715.1575

Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April

2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation). (2016, April).

Rietveld, S., & van Beest, I. (2007). Rollercoaster asthma: When positive emotional stress interferes with dyspnea perception. *Behaviour Research and Therapy*, *45*(5), 977–987. doi: 10.1016/j.brat.2006.07.009

Roller coaster elements. (n.d.). In *Wikipedia.* Retrieved on December 20, 2018, from https://en.wikipedia.org/w/index.php?title=Roller_coaster_elements&oldid=873357699

Roscoe, A. H. (1992). Assessing pilot workload. Why measure heart rate, HRV and respiration? *Biological Psychology*, *34*(2), 259–287. doi: 10.1016/0301-0511(92)90018-P

Shaffer, F., McCraty, R., & Zerr, C. L. (2014). A healthy heart is not a metronome: An integrative review of the heart's anatomy and heart rate variability. *Frontiers in Psychology*, *5*. doi: 10.3389/fpsyg.2014.01040

Shimmer. (2017). *Consensys* [Software]. Retrieved from http://www.shimmersensing.com/support/wireless-sensor-networks-download/

Taylor, S., & Jaques, N. (2016). *EDA-Explorer* [Python package]. Retrieved from https://github.com/MITMediaLabAffectiveComputing/eda-explorer

Taylor, S., Jaques, N., Chen, W. V., Fedor, S., Sano, A., & Picard, R. W. (2015). Automatic identification of artifacts in electrodermal activity data. *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 1934–1937. doi: 10.1109/EMBC.2015.7318762

van Gent, P., Farah, H., Nes, N., & van Arem, B. (2018). Heart Rate Analysis for

Human Factors: Development and Validation of an Open Source Toolkit for Noisy Naturalistic Heart Rate Data. *Proceedings of the 6th HUMANIST Conference*, 173–178.

Wade, M. G., & Jones, G. (1997). The Role of Vision and Spatial Orientation in the Maintenance of Posture. *Physical Therapy*, *77*(6), 619–628. doi: 10.1093/ptj/77.6.619

Yamaguchi, M., Kanemaru, M., Kanemori, T., Mizuno, Y., & Yoshida, H. (2003). Salivary amylase activity monitor used for stress evaluation. In *Proceedings of the 25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (Vol. 4, pp. 3075–3078). doi: 10.1109/IEMBS.2003.1280791

Appendix A

Informed Consent of the VR study

Consent Form for *Riding the virtual roller coaster*

YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM

Thank you for participating in my study. You can ask questions at any time and have a right to have them answered as far as they relate to the study and do not interfere with the measure. In the latter case they will be answered at a later moment.

My name is Luise Warnke. As part of my Master project I try to understand how persons react to roller coasters. During this session you will be watching four different VR simulations. While this you some physiological variables will be measured from your fingers. To assure that the measurements are good I would like to ask you to keep your arms as still as possible. After the simulation you will be asked some questions on demographics and about the simulation. In total the study will take about 20 minutes. By participating you are entitled to receive a compensation of 0.5 European Credit Points.

Due to known adverse effects it is strongly advised not to participate if you have a known history of fear of heights or strong motion sickness during roller coaster rides or you feel sick or distressed while watching VR. If during the session you feel distressed or sick, please, indicate this to the researcher. You will not be penalized for refusing or discontinuing participation.

Any personal information that is obtained during the study will be treated confidentially. If during the session you make utterances that are essential to the study's outcome you might be quoted in an indirect and anonymized manner. Datasets obtained by the wristband do not contain personal information and might be shared in their original form to inform future research or to validate results but might not be reported to serve any other goal than that of the research at hand. Results will be reported in my Master thesis and will be made accessible via the University of Twente library service (https://essay.utwente.nl/).

Your participation in this study is voluntary. You have the right to refuse participation. Also you have the right to withdraw consent at any moment. After withdrawal no further data will be collected or data collected after withdrawal will be erased. Data collected before withdrawal can be used, however.

This thesis project is supervised by Rob van der Lubbe (r.h.j.vanderlubbe@utwente.nl) and Matthijs Noordzij (m.l.noordzij@utwente.nl). They are therefore granted full insight in any data collected as part of the study.

If, after the session, you have any questions or remarks regarding the procedure or content of the study feel free to contact me at l.warnke@student.utwente.nl.

UNIVERSITY OF TWENTE.

Please, give your consent by crossing the corresponding box and signing on the last page of this document.

	Yes	No
Taking part in the study		
I have read and understood the study information provided above, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason or being susceptible to any penalization.	☐	☐
I understand that taking part in the study involves continuous measurement of heart rate and skin conductance.	☐	☐
I understand that the material used in this study can invoke feelings of fear (e.g. vertigo) or discomfort (e.g. motion or cybersickness).	☐	☐
Use of the information in the study		
I understand that information I provide will be used as a part of psychological research and scientific reporting.	☐	☐
I understand that personal information collected about me that can identify me, such as my name, will not be shared beyond the study team.	☐	☐
I agree that comments regarding the procedure I give orally (e.g. reporting sickness) can be quoted in research outputs.	☐	☐
Future use and reuse of the information by others		
I give permission for the heart rate and skin conductance data and any derived datasets to be stored on the researchers' personal computers and invited-access Google Drive so it can be used for future research and learning.	☐	☐

Contact Information for Questions about Your Rights as a Research Participant

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researchers, please contact the Secretary of the Ethics Committee of the Faculty of Behavioural, Management and Social Sciences at the University of Twente by ethicscommittee-bms@utwente.nl

Signature

___________________________ ___________________________ ___________

Name	Signature	Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Luise Warnke l.warnke@student.utwente.nl	Date

Appendix B

Demographics Questionnaire of the VR study

Participant ……

Demographics and experience

Fold twice after filling in.

What is your age? ……...

What is your gender?
- ☐ male
- ☐ female
- ☐ other/prefer not to answer

Do you usually experience motion sickness when going by car or riding a roller coaster?
- ☐ yes
- ☐ no

Do you usually suffer from vertigo/fear of height?
- ☐ yes
- ☐ no

Did you experience any strong feeling of sickness, discomfort or vertigo during the simulation?
- ☐ yes
- ☐ no

How did you feel about the roller coasters?

happy	scared
☐ very much	☐ very much
☐ a little bit	☐ a little bit
☐ not at all	☐ not at all

Do you recall being in one of the roller coasters you just saw?
- ☐ yes, please indicate which one(s):
  - ☐ first
  - ☐ second
  - ☐ last
- ☐ no

Appendix C

Events in VR videos

Table C1
Mammut

Tag	Event Marker (s)
Start	0.0
Drop	27.05
Lift hill	35.35
First drop	62.37
Helix	68.85
Hop	76.16
Helix	78.12
Hop	86.99
Helix	88.80
Hop	94.70
Helix	101.45
Tunnel	109.83
End brake	115.04
End	178.22

Table C2
Baron 1898

Tag	Event Marker (s)
Start	0.0
Lift hill	62.29
Brake	85.52
First drop	87.70
Tunnel	90.53
Immelmann	91.74
Roll	96.41
Helix	101.53
Hop	110.16
End brake	114.79
End	147.50

Table C3
Big Loop

Tag	Event Marker (s)
Start	0.0
Drop	3.94
Lift hill	15.81
First drop	52.08
Loop	59.00
Loop	62.94
Corkscrew	71.57
Corkscrew	74.12
Helix	86.36
End brake	95.16
End	114.40

Appendix D

Controller for the VR glasses

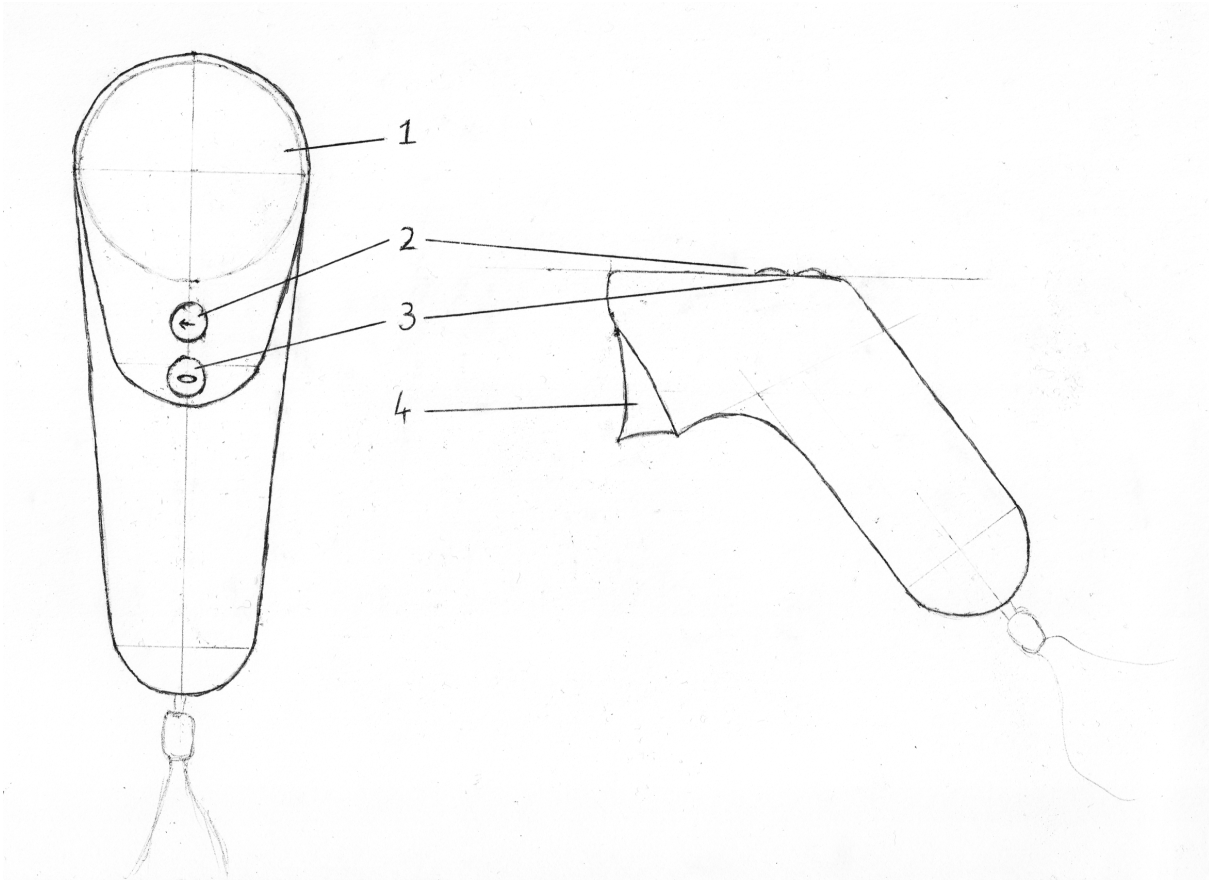

Figure D1. Controller for the VR glasses. Control elements: (1) touchpad for fine cursor controls; (2) back button; (3) “Oculus” button; (4) trigger. After putting on the Oculus Go, the controller needs to be pointed straight ahead and then be calibrated by pressing and holding the “Oculus” button (3). Hereby the device is unlocked. The following instructions given by the researcher should be carried out using the trigger (4). However, many participants erroneously pressed the back button (2) which is located next to the “Oculus” button (3).

Appendix E

Variables measured by the sensors of ShimmerGSR

Measurement	Unit
Unix Timestamp	ms
Acceleration	m/s^2
Skin Conductance	µS
Skin Resistance	kΩ
PPG	mV
Interbeat Interval (IBI)	ms
Heart Rate (HR)	BPM
Pressure	kPa
Temperature	°C

Appendix F

Code samples

Sample 1 - Processing of heart rate data

```
import heartpy as hp

def replace(data, sampleRate):
    working_data, measures = hp.process(data, sampleRate, bpmmax
       =220)
    peaks = working_data['peaklist']

    prev_loc = 0
    hr_list = []
    ibi_list = []

    for loc in peaks:
        frame = loc - prev_loc

        hr = 60/(frame/sampleRate)
        hr_list.extend([hr]*frame)

        ibi = (frame/sampleRate)*1000
        ibi_list.extend([-1.0]*(frame-1)+[ibi])

        prev_loc = loc

    hr_list.extend([hr]*(len(data) - prev_loc))
    ibi_list.extend([-1.0]*(len(data) - prev_loc))

    return hr_list, ibi_list
```

Sample 2 - Segmentation for replication

```
import os
import file_manipulation as files

def segment(filepath, sampleRate, segments, study, Shimmer = True
    , folder=None):
    if Shimmer:
        filelist = os.listdir(os.path.abspath(filepath+'\\clean')
           )
    else:
        filepath = os.path.join(filepath, folder)
        filelist = os.listdir(filepath)
    headers = ["Participant","Video","Condition","Segment","
       HR_avg","HR_max","SCR","SCL"]
```

```python

    var_list = []
    for file in filelist:
        if file.startswith("Part"):
            try:
                if Shimmer:
                    data = files.load(os.path.abspath(filepath+'\\clean\\'+file))
                    condition = int(re.search('Condition(.+?).csv',file).group(1))
                    part = int(re.search('Participant(.+?)_',file).group(1))
                    peak_data = files.load(os.path.abspath(filepath+'\\peaks\\Peaks_Part'+str(part)+".csv"))
                else:
                    data = files.load(os.path.join(filepath,file))
                    condition = 0
                    part = int(re.search('Id(.+?)\.csv',file).group(1))
                    part_name = re.search('Part(.+?)_',file).group(1)
                    peak_data = files.load(os.path.abspath(r"C:\\Users\\louwa\\Documents\\Python Master\\Project Files\\data\\peaks\\"+folder+"\\Peaks_Part"+str(part)+".csv"))

                seg = 0
                for i in segments:
                    for j in range(0, segments[seg][2]):
                        if segments[seg][0] == "base":
                            video = 0
                            start = start_base*60*sampleRate
                        else:
                            if Shimmer:
                                video = VIDEOS[condition][j]
                            else:
                                video = folder[-1]
                            start = data[data["Tag"]==segments[seg][0]].iloc[j].name
                            try:
                                start = data.index.get_loc(start).start
                            except AttributeError:
                                start = data.index.get_loc(start)
                        end = data[data["Tag"]==segments[seg][1]].iloc[j].name
                        try:
                            end = data.index.get_loc(end).start
                        except AttributeError:
```

```
                            end = data.index.get_loc(end)
                        if segments[seg][0] != "base" or Shimmer:
                            frame = data.iloc[start:end]
                            starttime = data.iloc[start].name
                            endtime = data.iloc[end].name
                            mask = (peak_data.index >= starttime)
                                & (peak_data.index <= endtime)
                            scr_peak = peak_data.loc[mask]
                            scr = (len(scr_peak) / float(len(
                               frame)/sampleRate)) * 60
                        else:
                            frame = files.load(os.path.abspath(r'
                               C:\\Users\\louwa\\Documents\\Python
                               ␣Master\\Project␣Files\\data\\clean
                               \\Baseline\\Part'+part_name+'_Id'+
                               str(part)+".csv"))
                            base_peak = files.load(os.path.
                               abspath(r'C:\\Users\\louwa\\
                               Documents\\Python␣Master\\Project␣
                               Files\\data\\peaks\\Baseline\\
                               Peaks_Part'+str(part)+".csv"))
                            scr = (len(base_peak) / float(len(
                               frame)/sampleRate)) * 60
                        HR_avg = frame["HR"].mean()
                        HR_max = frame["HR"].max()
                        scl = frame['filtered_eda'].mean()
                        var_list.append([part, video, condition,
                           seg, HR_avg, HR_max,scr,scl])
                    seg += 1
            except IndexError:
                print("Participant", part, "failed")
    files.save(var_list, headers, "Participant", "data\\"+study+"
       \\Segments")
```

Sample 3 - Find anchors for tagging of E4 data

```
def find_start(data, sampleRate, window = 5, shift = 2):
    for col in data.columns:
        data[col] = files.butter_lowpass_filter(data[col], 1,
           sampleRate)
    data["Acc"] = ((data["WideX"]**2+data["WideY"]**2+data["WideZ
       "]**2)**0.5)-9.81
    found = False
    i=0
    start_time = data.index[0]

    while found == False:
        if i*(shift*sampleRate)+(window*sampleRate) < len(data):
            dat = data.iloc[i*(shift*sampleRate):i*(shift*
```

```
                sampleRate)+(window*sampleRate)]
            if abs(dat.Acc.mean()) >1.0:
                found=True
                return (start_time + pd.to_timedelta((i*shift+int(0.5*window)), unit = 's'))
            else:
                i+=1
        else:
            print("None found")
```

Appendix G

Adaptions made in Taylor and Jaques's (2016) EDA-Explorer [6]

Changes in `EDA-Artifact-Detection-Script.py`

Line	Original	Adapted
16	`def getWaveletData(data):`	`def getWaveletData(data, sampleRate):`
...		
37	`N = int(len(data)/8)`	`N = int(len(data)/sampleRate)`
...		
45	`N = int(np.floor((len(data)/8.0)*2))`	`N = int(np.floor((len(data)/sampleRate)*2))`
...		
120	`def createFeatureDF(data):`	`def createFeatureDF(data, sampleRate):`
...		
129	`wave1sec,waveHalf = getWaveletData(data)`	`wave1sec,waveHalf = getWaveletData(data, sampleRate)`
...		
132	`timestampList = data.index.tolist()[0::40]`	`timestampList = data.index.tolist()[0::5*sampleRate]`
...		
200	`def classify(filepath, classifierList, loadDataFunction):`	`def classify(filepath, classifierList, sampleRate):`
...		
213	`oneHour = 8*60*60 # 8(samp/s)*60(s/min)*60(min/hour) = samp/hour`	`oneHour = sampleRate*60*60 #(samp/s)*60(s/min)*60(min/hour) = samp/hour`
214	`fiveSec = 8*5`	`fiveSec = sampleRate*5`

Changes in `EDA-Peak-Detection-Script.py`

Line	Original	Adapted
11	`def findPeaks(data, offset, start_WT, end_WT, thres=0, sampleRate=SAMPLE_RATE):`	`def findPeaks(data, offset, start_WT, end_WT, thres=0, sampleRate):`
...		
141	`def calcPeakFeatures(data, outfile,offset,thresh,start_WT,end_WT):`	`def calcPeakFeatures(data, outfile,offset,thresh,start_WT,end_WT, sampleRate):`
142	`returnedPeakData = findPeaks(data, offset*SAMPLE_RATE, start_WT, end_WT, thresh, SAMPLE_RATE)`	`returnedPeakData = findPeaks(data, offset*sampleRate, start_WT, end_WT, thresh, sampleRate)`

[6] The line numbers and code is taken from the March 16, 2019 upload of the script.

Appendix H

Plots of data analysis for VR study

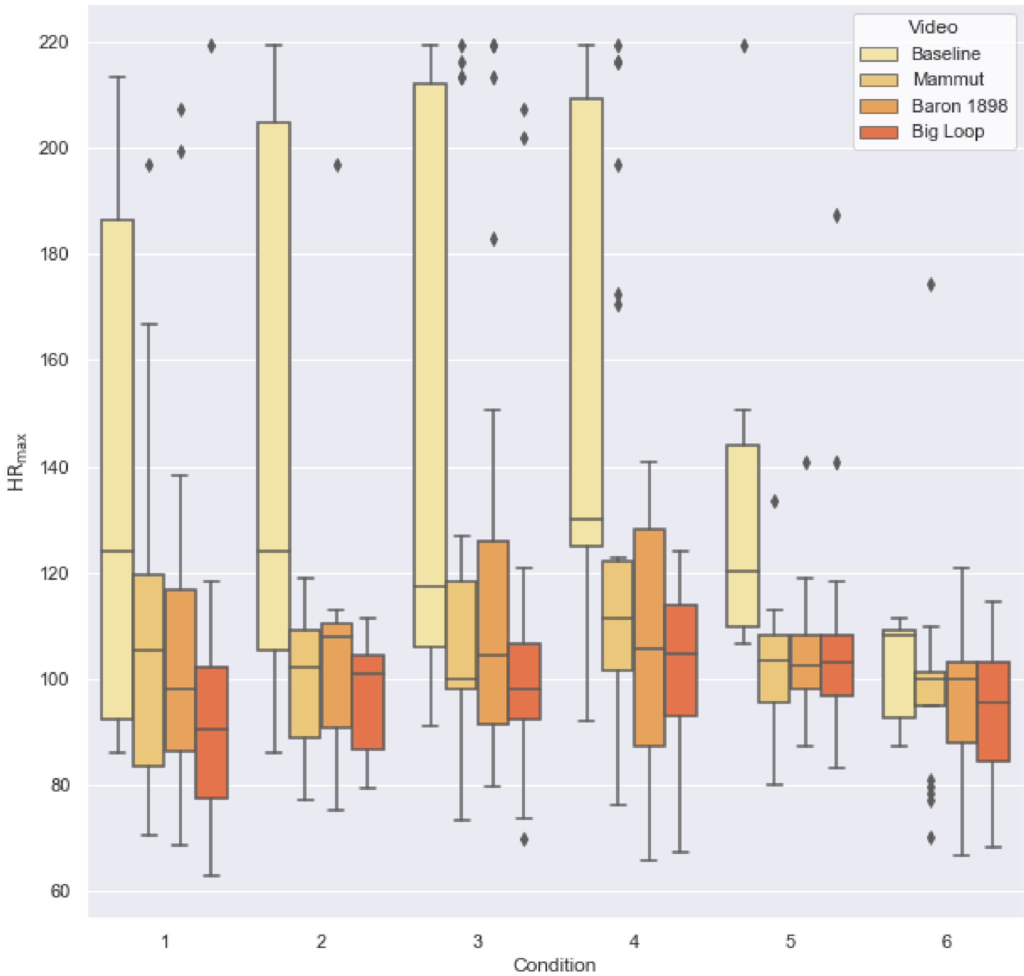

Figure H1. Time-normalized maximum heart rate by video for each condition.

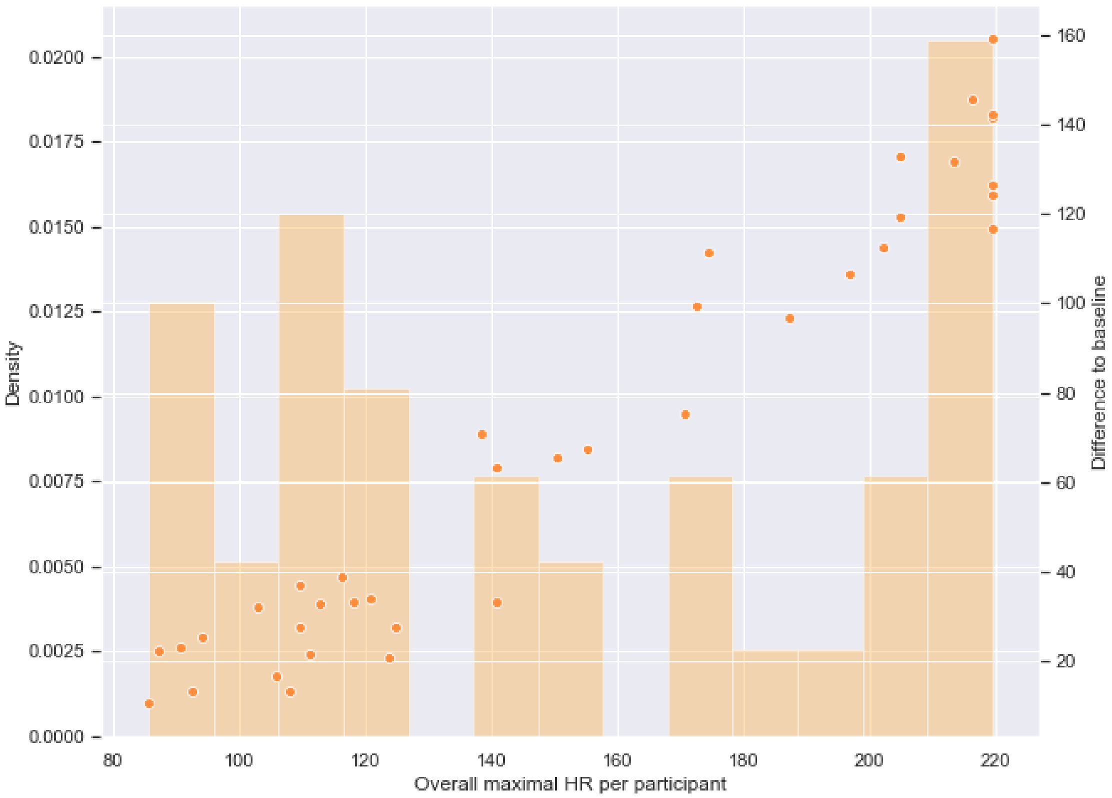

Figure H2. Overall time-normalized maximum heart rate per participant and its distance to the participant's baseline heart rate.

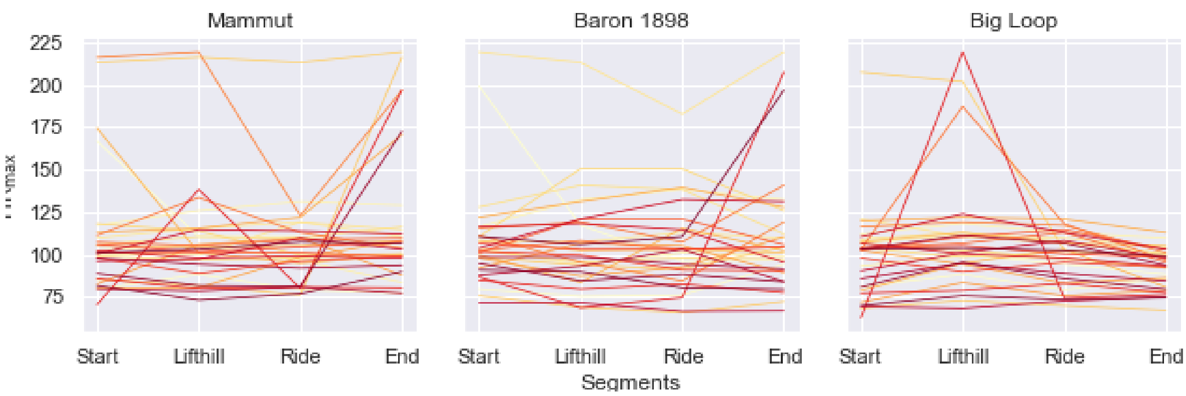

Figure H3. Time-normalized maximum heart rate for each segment and participant by video.

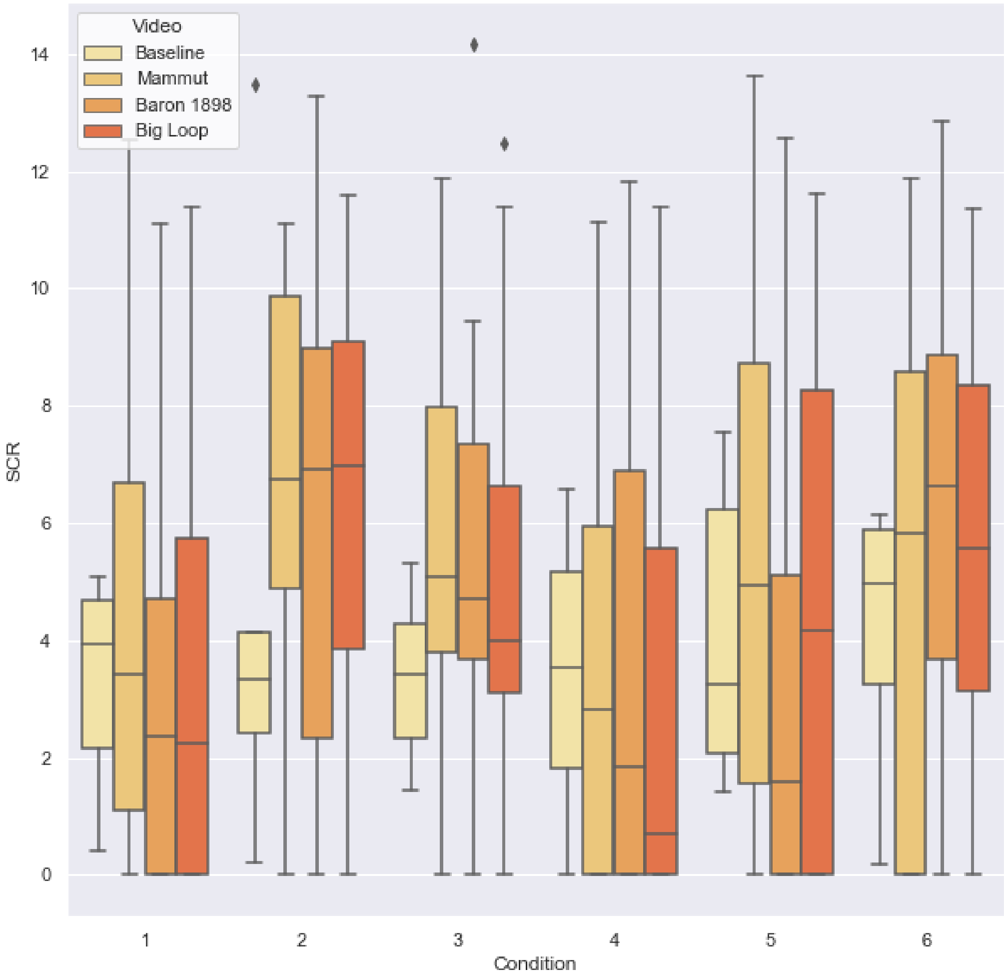

Figure H4. Number of SCR per minute by video for each condition.

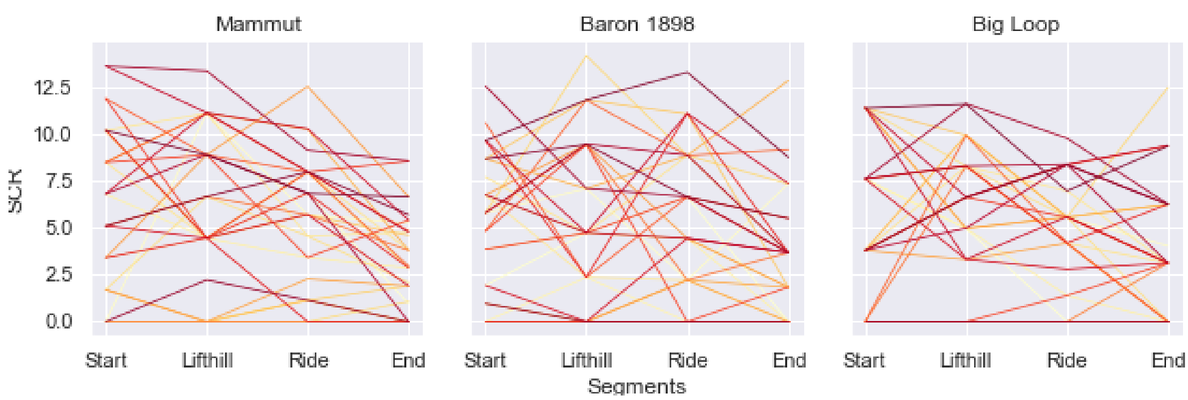

Figure H5. Number of SCR per minute for each segment and participant by video.

Appendix I

Informed Consent of the real-world study

Consent Form

YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM

Thank you for participating in my study. You can ask questions at any time and have a right to have them answered as far as they relate to the study and do not interfere with the measure. In the latter case they will be answered at a later moment.

My name is Luise Warnke. As part of my Master project I try to understand how people react to roller coasters. During your visit to the Efteling you will be wearing a wristband which will measure physiological data. To assure that the measurements are good I would like to ask you to keep your arms as still as possible. After signing this form you will be asked some questions on your demographic background. The test will stop when you leave the park or you decide to stop participation.

Due to known adverse effects it is strongly advised not to participate if you have a known history of fear of heights or strong motion sickness during roller coaster rides. If you feel distressed or sick, please indicate this to the researcher. You will not be penalized for refusing or discontinuing participation. Furthermore, you cannot participate if you have a known heart disease, pregnancy or experienced severe back problems in the past.

Any personal information that is obtained during the study will be treated confidentially. If during your participation you make utterances that are essential to the study's outcome you might be quoted in an indirect and anonymized manner. Datasets obtained by the wristband do not contain personal information and might be shared in their original form to inform future research or to validate results but might not be reported to serve any other goal than that of the research at hand. Results will be reported in my Master thesis and will be made accessible via the University of Twente library service (https://essay.utwente.nl/).

Your participation in this study is voluntary. You have the right to refuse participation. Also you have the right to withdraw consent at any moment. After withdrawal no further data will be collected or data collected after withdrawal will be erased. Data collected before withdrawal can be used, however.

This thesis project is supervised by Rob van der Lubbe (r.h.j.vanderlubbe@utwente.nl) and Matthijs Noordzij (m.l.noordzij@utwente.nl). They are therefore granted full insight in any data collected as part of the study.

If, after the session, you have any questions or remarks regarding the procedure or content of the study feel free to contact me at l.warnke@student.utwente.nl.

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Appendix J

Variables measured by the sensors of Empatica E4

Measurement	Unit	Sampling Rate
Acceleration	$1/64g$	32 Hz
PPG	nW	64 Hz
Skin Conductance	μS	4 Hz
Interbeat Interval (IBI)	s	dependent on HR
Heart Rate (HR)	BPM	1 Hz
Temperature	°C	4 Hz

Appendix K

Plots of data analysis for park study

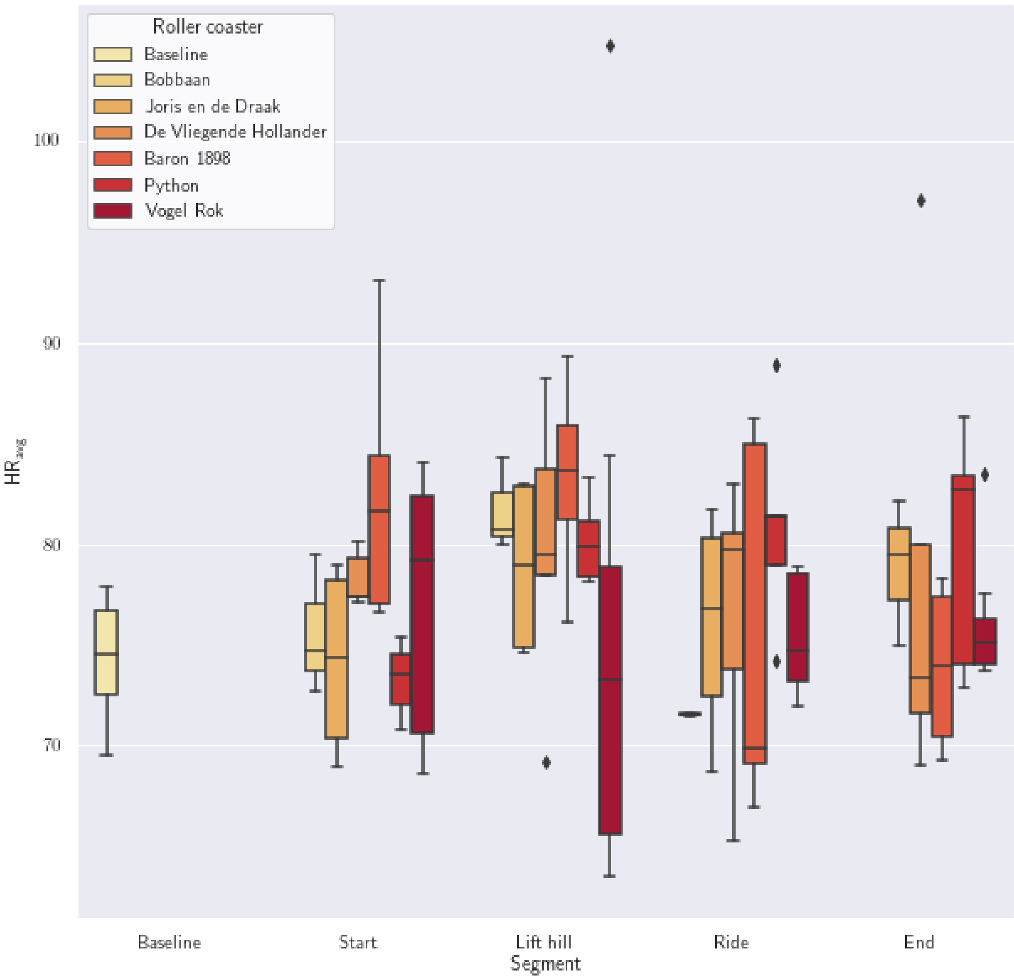

Figure K1. Average heart rate split by roller coaster for each phase.

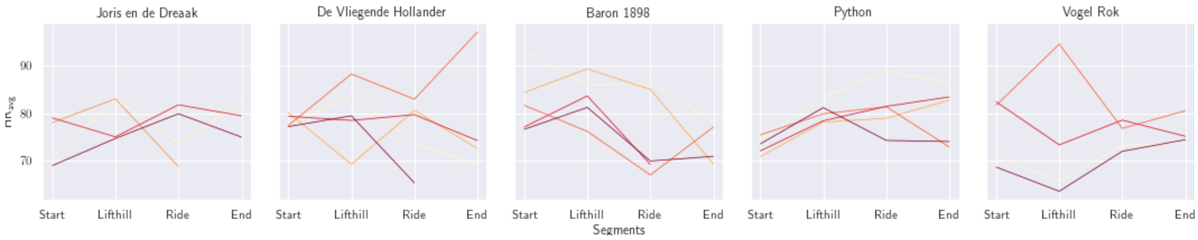

Figure K2. Average heart rate per participant and roller coaster.

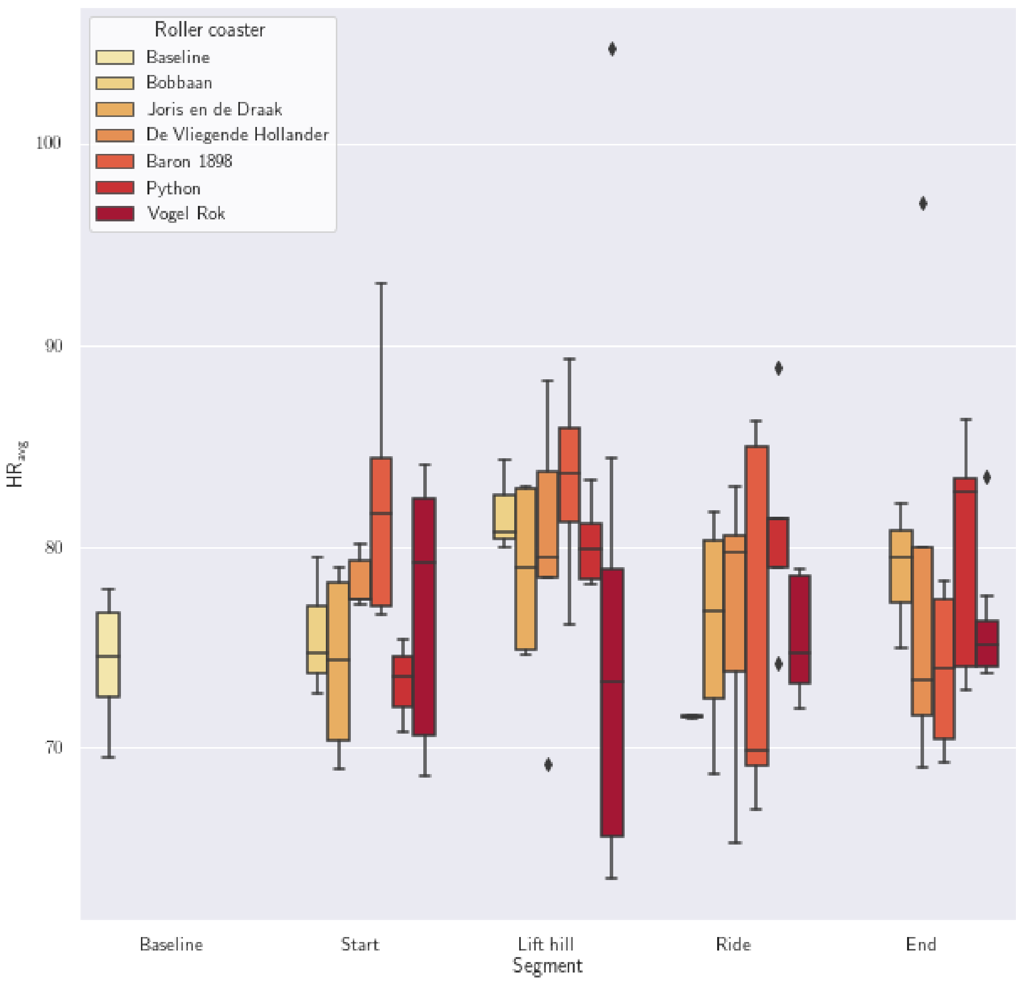

Figure K3. Number of SCR per minute split by roller coaster for each phase.

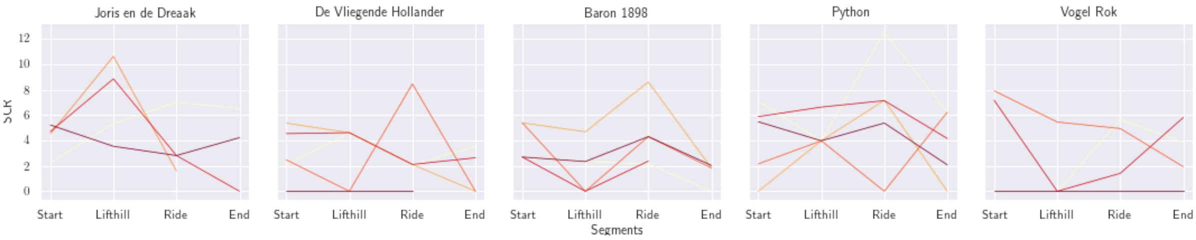

Figure K4. Number of SCR per minute per participant and roller coaster.

Appendix L

Full HR and EDA diagrams for park study

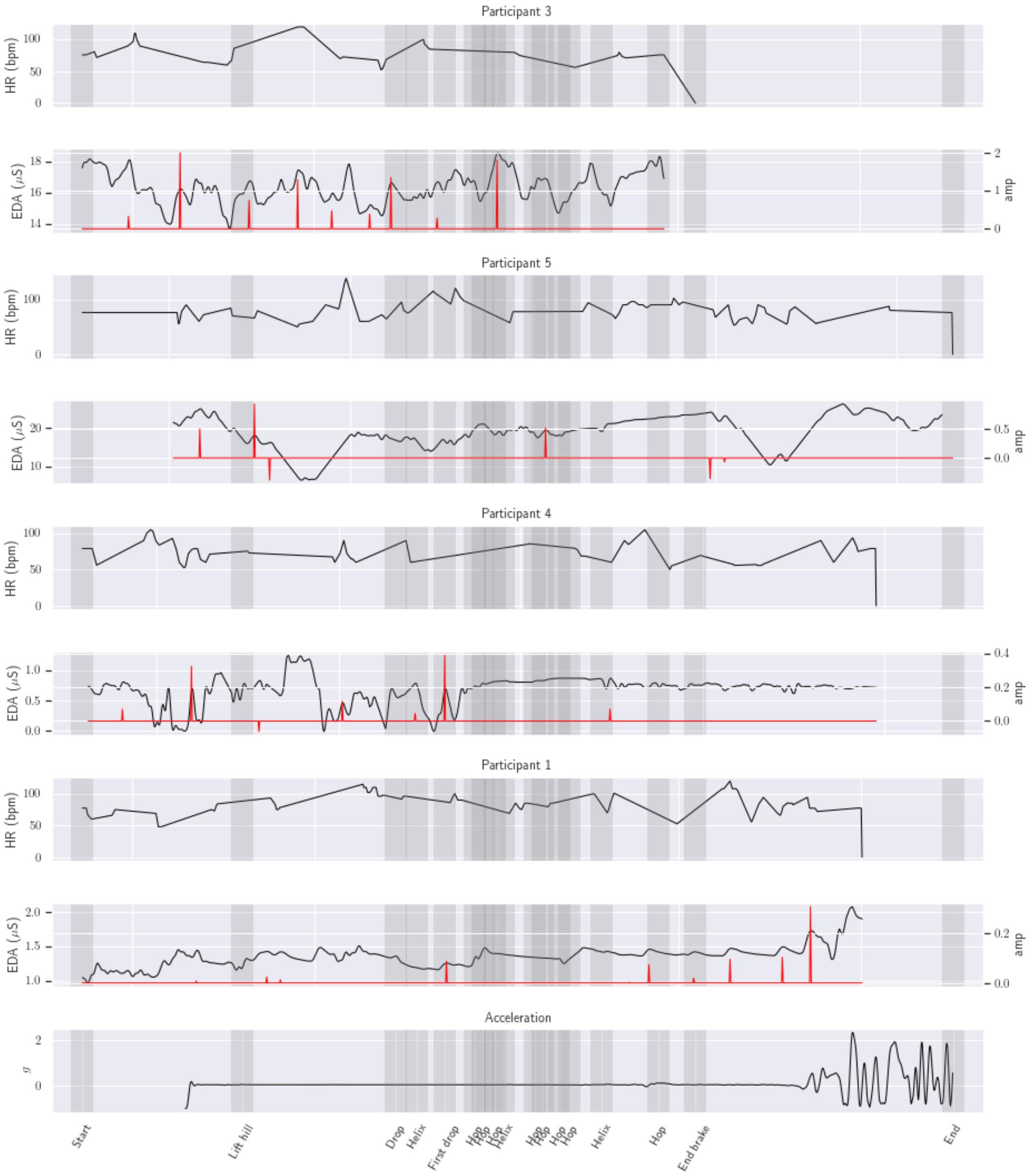

Figure L1. Joris en de Draak

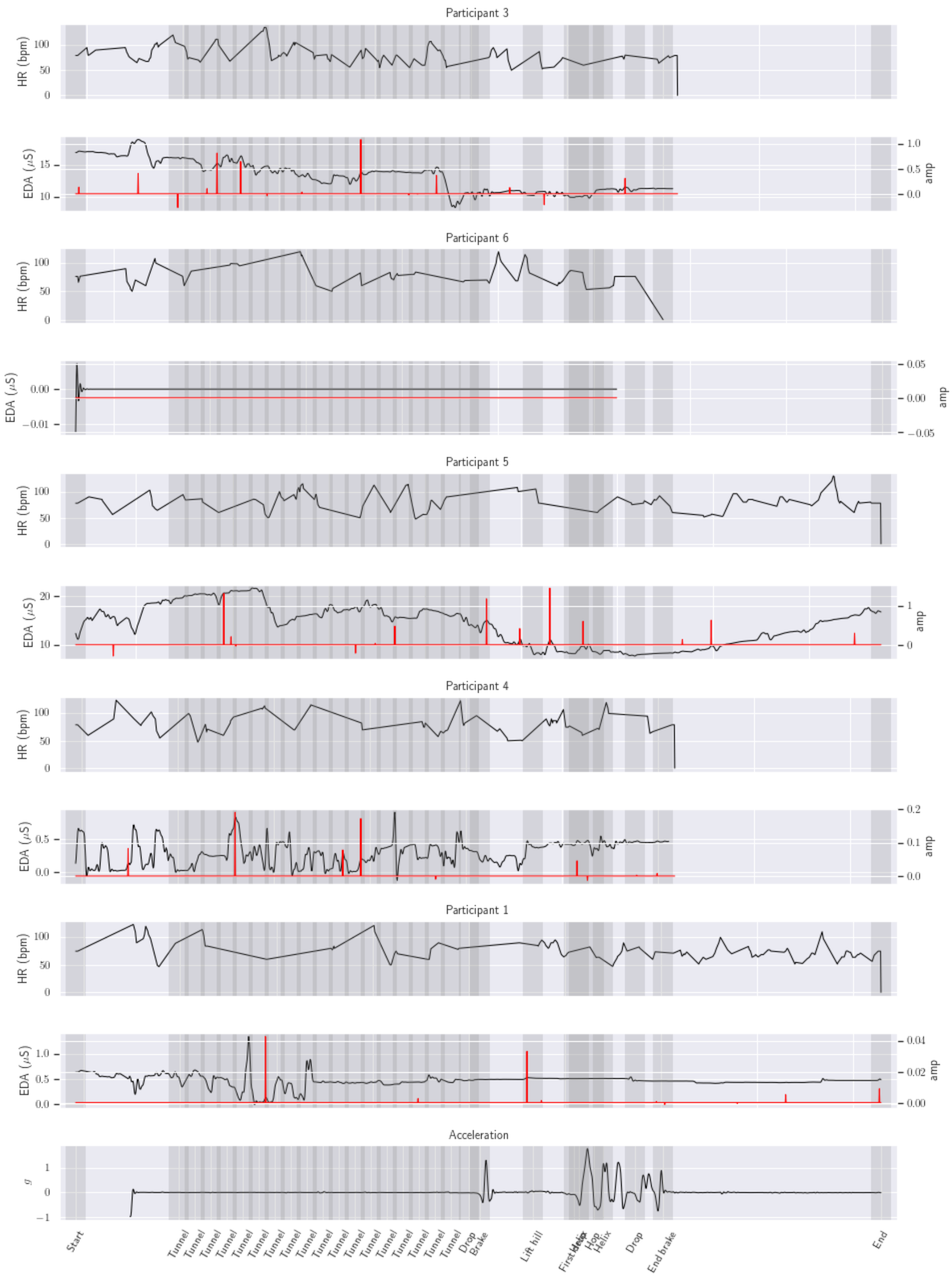

Figure L2. De Vliegende Hollander

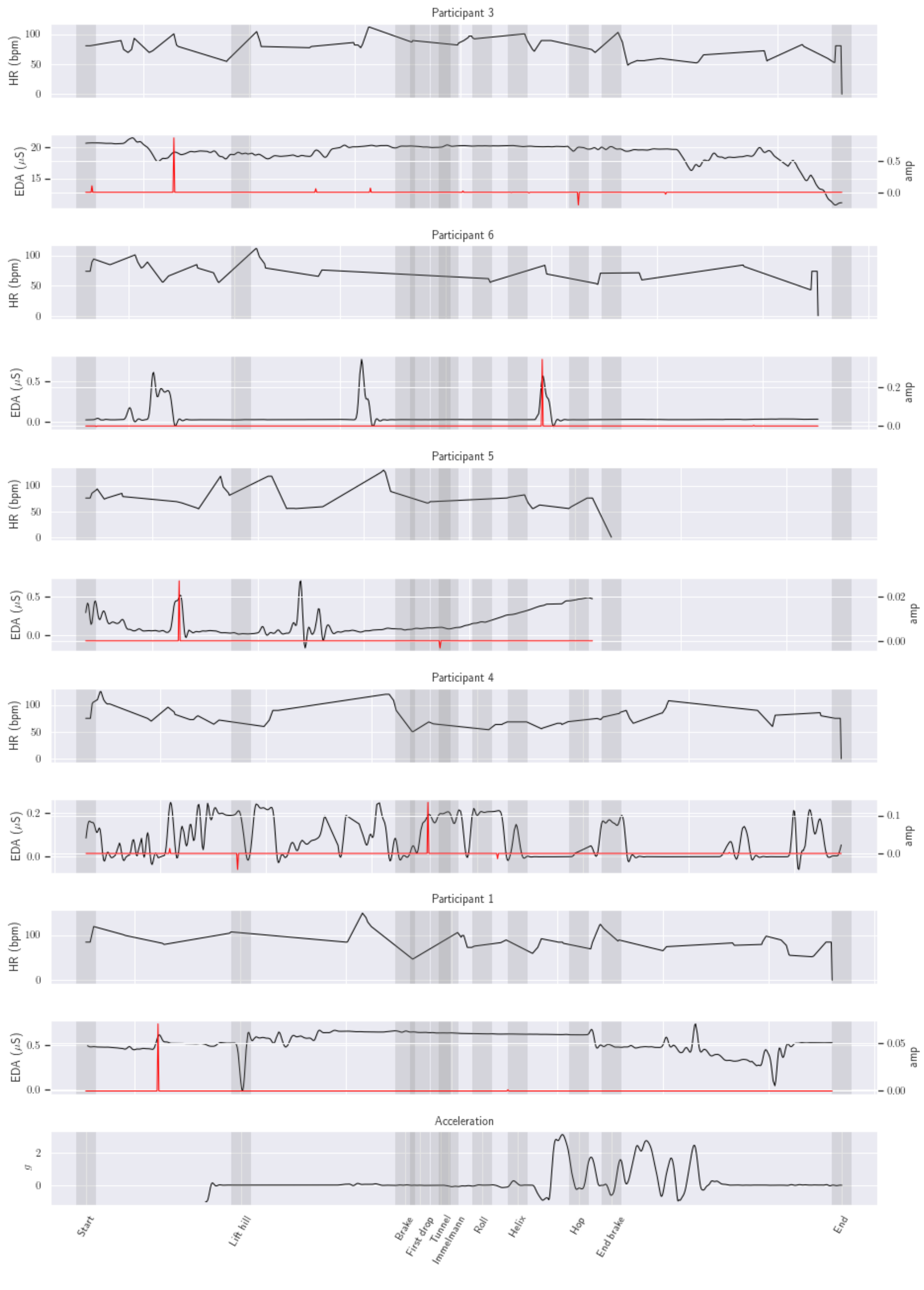

Figure L3. Baron 1898

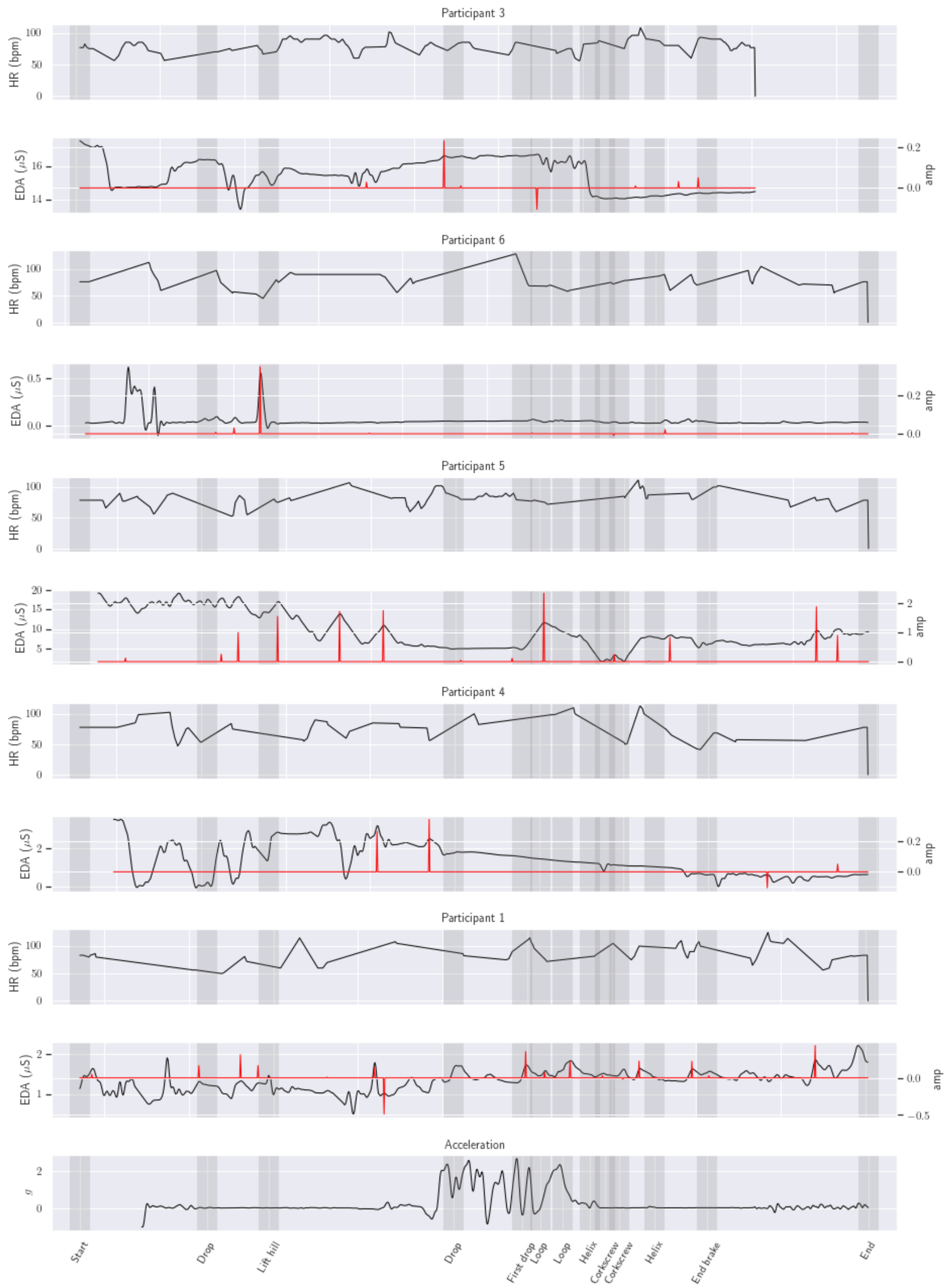

Figure L4. Python

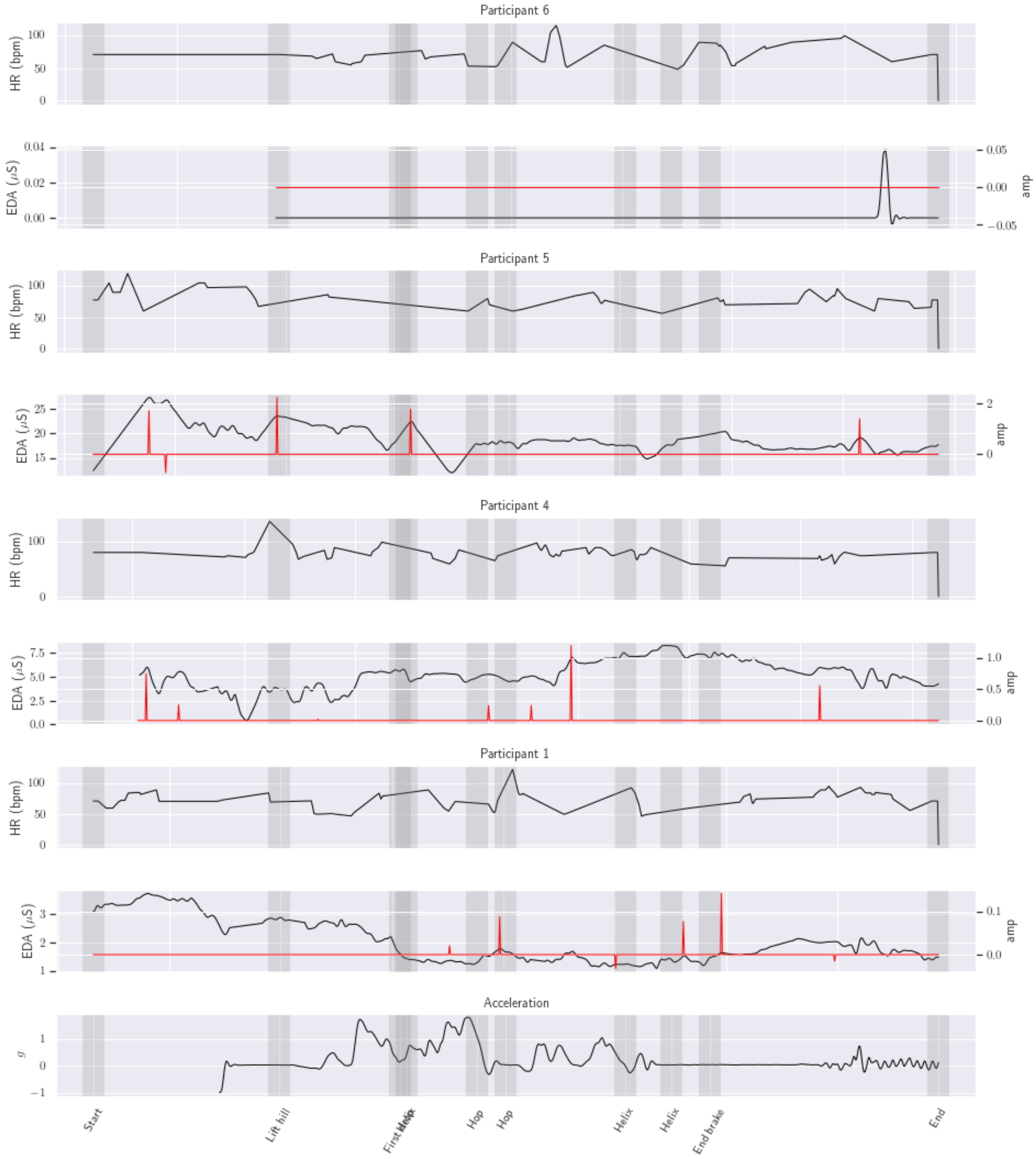

Figure L5. Vogel Rok 1

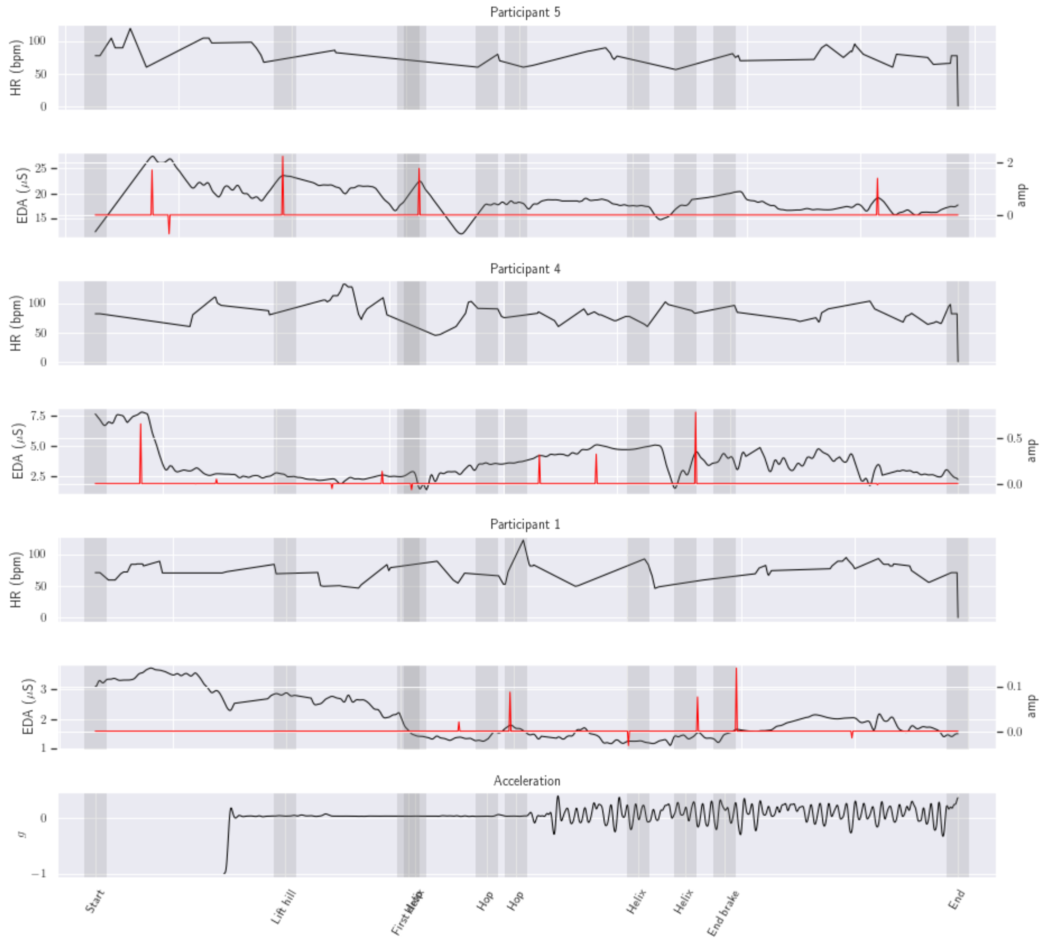

Figure L6. Vogel Rok 2