Pace yourself! The effects of optic flow on biomechanics of movement and perceived effort

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Optic flow is fundamental for motor control and impacts the way we take and perform actions. Yet, little is known about how natural changes of optic flow might impact our behaviour and how we experience it. In this study we aim to answer two research questions: *1) How do changes in optic flow density impact the biometric parameter of cycling cadence? 2) How do natural changes of optic flow impact how we perceive effort?* Two experiments were designed to explore these phenomena. In both experiments, participants were asked to cycle in virtual reality through four different optic texture conditions. The used textures were different in both experiments (simple textures in Experiment 1 and natural, complex textures in Experiment 2), but their placement and frequency in the scene were maintained. The results showed no significant difference in mean pedalling cadence between texture conditions, but participants perceived movement speed differences in different texture conditions. Furthermore, the results showed differences in perceived effort between texture conditions and experiments. Surface optical density was the optic flow descriptor with the largest change between experiments and is at least partially responsible for the changes in perception. The results also suggest an impact of factors specific to each individual. Further analysis should be done on the dataset to describe these relationships in more detail and account for their impact.

CCS Concepts: • **Human-centered computing → HCI theory, concepts and models**; *User studies.*

Additional Key Words and Phrases: optic flow, visual flow, virtual reality, cycling, perception-action coupling, psychological flow, biomechanics of movement

1 INTRODUCTION

Optic flow is the expanding pattern of light on the retina that changes systematically to reflect a person's movements through an environment [Fajen 2021; Parry et al. 2012; Warren and Rushton 2009]. Optic flow is fundamental for motor control [Fajen 2005; Mohler et al. 2007; Postma et al. 2017; Warren et al. 2001]. Optic flow provides the basis for controlling interceptive behaviour like catching a fly ball [Postma et al. 2017], navigation [Warren et al. 2001], preferred speed of motion [Mohler et al. 2007] and others. Yet, little is known about how natural changes of optic flow might impact the way we control behaviour and experience it. This might have implications for the way we understand fundamental research about motor control and might also have implications for the way we design environments for sports, exercises and activities. In this study, we investigate *1) How do changes in optic flow density impact the biometric parameter of cycling cadence? 2) How do natural changes of optic flow impact how we perceive effort?*

The research project covers three interacting areas - optic flow, biomechanics of movement and psychological flow. The previously described phenomena can be described as a system where the optic flow is the input variable and the biomechanics of movement and the psychological flow are the outputs.

1.1 Optic flow

The project aims to understand the effects of natural changes of optic flow and thus a clear definition of natural changes of optic flow is needed. Natural changes of optic flow during this study are defined as the changes in scenery that occur while people move through a natural environment while engaging in an endurance-based activity. Walking, running, rowing and cycling are examples of such endurance-based activities. Global optical flow rate *(Global optical flow rate (GOFR) [Larish and Flach 1990; Warren 1982] is the velocity of forward motion scaled in altitude units)* for such activities is mostly dependant on the velocity of the forward motion as the changes in person's eye height are usually negligible.

Cycling allows for the largest relative change in eye height as the person can lean forwards or sit up straight, but even then people usually pick their cycling position and stay in it for a while. During endurance-based activities people do not make large and frequent variances of their speed, thus GOFR stays largely constant throughout the activity. Surface optical density *(Surface optical density (SOD) is defined by the authors of this study as an extension to global optical density defined by Warren [1982]. SOD is the distance to surface divided by surface texture element size.)*, on the other hand, is fully dependent on the distance to surface and surface texture and can show large differences between different natural environments. For example, on a forest road, the distance to trees is much smaller than when the trees are at a far distance (or not present in the scene) while cycling through flatlands. Thus, SOD is much higher in the forest compared to the flatlands. Differences between dense and less dense forests or flatlands also result in large edge rate variations *(Edge rate (ER) [Fajen 2005; Larish and Flach 1990; Warren 1982] is described as the number of objects passing a fixed reference point in units of time)*. In the case of a forest, ER can be seen as the rate at which a person passes trees. With smaller distances between trees and/or higher movement speeds, the ER will increase. All in all, natural changes of optic flow can be described by a small variation in GOFR and a large variation in SOD and ER.

Another key characteristic of the natural changes of optic flow is the gradual transitions between environments. When going on a straight road, people will first see the new scenery in a far distance. As they continue to move forward, the distance to the new scenery gradually decreases until they are surrounded by it.

While conducting research on optic flow, researchers often need to induce changes in optic flow. That said, there is no single way how to vary optic flow in a consistent manner. During the previous research on optic flow, the optic flow has been varied in multiple different ways with two approaches being the most prominent. In the first approach, optic flow is seen as a video which captures what a person sees while moving through an environment [Mohler et al. 2004, 2007; Parry et al. 2012]. Subsequently, this video is played in front of the participant with varying playback speeds. This approach introduces a mismatch between the movement speed in the optical flow video and the person's actual velocity of forward motion. When playback speed is varied, it also proportionally changes GOFR and ER, but has no effect on SOD. As discussed previously, during natural changes of optic flow, a small variation in GOFR and large variation in SOD and ER can be observed, thus the approach of varying optic flow video playback speed does not accurately simulate the effects of natural changes of optic flow.

The second widely used approach to change optic flow during research is by varying number of edges in the field of view [Fajen 2021; Larish and Flach 1990; Ludwig et al. 2018]. By doing so, the GOFR is not impacted, but these variations are reflected in SOD and ER which is in line with the principles of natural changes of optical flow. That said, during the previous optical flow research, oftentimes environments with relatively simple textures (and relatively low SOD) have been used [Larish and Flach 1990; Ludwig et al. 2018], but in real-life conditions, the textures can be relatively complex (high SOD), for example, a two-dimensional rectangle compared to a three-dimensional tree with individual leaves and branches.

1.2 Biomechanics of movement

Optic flow is one of the three interacting areas in this project. It can be seen as the input to the perception-action system which has biomechanics of movement and psychological flow as the outputs. So far we have defined what are the characteristics of natural changes of optical flow, but we also need to define these other two variables for this research.

During this study, biomechanics of movement is used to describe movement speed, cadence and posture during an activity. These measures allow assessing the effect of natural change of optic flow on performance. The project focuses on endurance-based activities. Each one has its pro's and con's when used for optic flow research. While the results of the research are applicable to endurance-based in general, experiments were designed around one activity which was deemed to be the most optimal for optic flow research using virtual reality technology in a lab setting. When thinking about endurance-based activities, walking, running and cycling stand out as the most popular ones. Rowing is also a relatively popular sport in the Netherlands (where the study takes place), but much fewer people engage in it compared to the other three. Walking and running can be seen as an extension of each other. At slower movement speeds person walks and once the gait transition point is reached, the person switches to running. The exact point of gait transition is individual and dependent on the situation [De Smet et al. 2009; Mohler et al. 2007] which can pose a challenge for research [Baumberger et al. 2000]. Baumberger et al. [2000] mention that in their previous studies with adults, the instructed and drilled walking speed was too high which negatively affected participants' ability to accelerate without starting to run. Due to this experience, during the following studies they asked participants to pick a comfortable pace which allowed for a symmetrical possibility to accelerate and decelerate. Cycling does not have a gait transition point and the relationship between cadence and movement speed is linear. Cyclist output power is a function of cycling cadence and the force applied to the pedals. The movement speed can be easily calculated from this relationship, but a separation has to be made between single-speed and geared bikes. The former has a fixed gear ratio between the pedal sprocket and wheel sprocket, thus effectively the movement speed has a linear relationship with pedalling cadence though out the whole range. In the case of the geared bikes, the ratio between sprockets can be changed throughout the activity to keep the cyclist at the optimal power band [Hoffman 2002] and thus the ratio between movement speed and pedalling cadence is not consistent throughout the activity.

Conducting experiments in a lab setting using virtual reality (VR) offers a multitude of benefits [Zeuwts et al. 2016], but it also comes with extra considerations regarding the activity of choice. VR allows to immerse participants in a tailor-made repeatable environments. It is possible to reproduce the same visual conditions between participants and to randomise the order of these conditions. This would not be possible, in a real-world environment. A treadmill or an exercise bike can be used to allow walking, running or cycling in one physical location. From a safety standpoint, an exercise bike is preferred over a treadmill as the risks of falling and injury are considerably lower. Studies [Kong et al. 2012; Mieras et al. 2014; Smith et al. 2001] show that people underestimate their speed in a lab environment compared to outdoor running and cycling and tend to move slower. That said, their perceived exertion was the same in both situations which could be explained by the lack of cooling airflow in the lab environment [Mieras et al. 2014]. All in all, cycling can be seen as a more suitable activity for this experiment due to the linear relationship between cadence and movement speed and the possibility to conduct VR cycling research with lower risks.

1.3 Psychological flow

Psychological flow is the third area of interest in this study. Psychological flow describes an enjoyable optimal experience which occurs while a person is fully engaged in an activity [Cheron 2016]. In the sports context, it is also considered to be the state of effortless, peak performance [Jackson et al. 2001]. In order for the psychological flow to occur, an activity has to have clear goals, clear and immediate feedback and the person's skills have to match the challenge. From these requirements, optic flow can impact the reception of clear and immediate feedback and the relationship between skill and challenge. Previous research shows that changes in optical flow affect the perception of self-motion [Fajen 2021] - a higher edge rate can be associated with higher perceived movement speed. This can create a mismatch between the optically perceived speed of self-motion and the internal frame of reference for specific action (pedalling speed versus how fast people see the environment going past). Furthermore, this mismatch can affect the perception of the challenge in the skill-challenge relationship. A higher optical flow rate makes the perceived speed of self-motion higher which consequently reduces the size of the challenge and vice versa.

A variety of validated psychological flow assessment questionnaires, such as the Flow State Scale, Dispositional Flow Scale [Jackson et al. 2001; Stoll 2019] and Flow Short Scale [Stoll 2019] can be used to determine the extent of flow experienced by the participant. These questionnaires assess a variety of factors associated with the state of flow but take some time to administer and thus are not ideal for periodical use during an experiment when the participant is cycling through a virtual reality environment. We can argue that the act of administrating such questionnaires during the experiment would have a significant impact on the experience as a whole and potentially affect the study results. Thus, for this type of study, a simpler and less intrusive proxy variable-based approach would be more desirable.

According to Mihaly Csikszentmihalyi [Csikszentmihalyi 2014], the ratio between skill and challenge is one of the core factors that enable the occurrence of psychological flow. We theorise that the interaction between optical flow and psychological flow affects this mechanism. Natural optical flow variations can affect the perceived size of a challenge which would affect the skill/challenge ratio and subsequently the sense of self-efficacy. To assess this aspect of psychological flow, rating of perceived exertion (RPE) was used as a variable that reflects the perceived extent of a challenge and heart rate measurements was used as the representative of the actual exertion. The Borg scale is an established scale for measuring RPE [Parry et al. 2012; Wilmore et al. 2012]. The original Borg scale associates the rating of perceived exertion with a score from 6 to 20 where 6 represents no effort and 20 is associated with maximum effort. The advantage of this scale is the ability to estimate the participant's heart rate directly from the score by multiplying the rating by 10 (8 on the Borg scale would represent an estimated heart rate of 80 bpm). That said, it is an unusual range and a variation of the Borg scale - Borg Category Ratio Scale (CR10) [Zamunér et al. 2011] - can be seen as more intuitive and easier to understand. The CR10 scale has a range of 0-10 where 0 represent no exertion and 10 is associated with the maximum effort. RPE is expected to increase over time independent of the actual performance [Parry et al. 2012]. That said, slower optic flow is expected to result in a slower rate of increase in RPE and vice versa.

1.4 Research scope

Previous studies have explored the relationship between optic flow, biomechanics of movement and psychological flow, but our focus on the natural change of optic flow sets this study apart. Parry et al. [2012] conducted a study to investigate the effects of optic flow on the perceived exertion during cycling. They asked participants to cycle a 20 km timed trial as fast as possible while being shown an optic flow video footage of a real road. While the research at its core is similar to this project, they varied optic flow by changing the optic flow video playback speed which is not in line with the principles of natural changes of optical flow. Furthermore, the researchers did not explore the effects of specific scenery on the participants' performance but looked at the effects of optic flow's relative speed. The current study aims to take these factors into consideration during the experiment design and explore their impact of them on the results. Parry et al. [2012] study results showed that a slower optical flow was associated with a lower rate of perceived exertion (RPE) and higher power output, but did not show any differences in heart rate or cadence. Since the participants used geared bikes and resistance was kept the same during the experiments, the higher power output can effectively be seen as a higher cycling speed. In Ludwig et al. [2018] study the optic flow was varied by changing the frequency of stripes on the ground which directly affected the edge rate. Results showed a small, but consistent inversely proportional effect of optical flow variations on preferred walking speed - participants' walking speed was slower when the strip frequency increased. This study used 12 meter long projected walkway and thus participants were continuously immersed in the environment for a small amount of time which is not the case when they are exposed to the natural environment.

Furthermore, the experiment environment had very low surface optical density (SOD) which is not in line with the high texture complexity present in some natural environments.

Less previous research has focused on the interaction between optic flow and psychological flow, but it offers some insights. While psychological flow was not the main focus of the study conducted by Baumberger et al. [2000], qualitative results of their study suggest some relationship between optic flow and psychological flow. In an approaching optic flow, participants felt that walking was more difficult, comparable to walking against a stream of water. Contrary, the receding optic flow felt easier and was associated with walking on a moving walkway which carried them forwards. The approach taken to vary optic flow does not follow the principles of the natural change of optic flow described earlier as they varied the direction of optic flow.

Our study sets itself apart from the existing research with an increased focus on the principles behind the natural changes of optical flow. We aim to bridge the gap between fundamental optic flow research and real-world environments and situations. Previous research on optic flow effects on biomechanics of movement oftentimes has been carried out using simple, unrealistic environments and has used approaches to vary optic flow in ways that cannot be replicated in the real world. Furthermore, the study aims to highlight the trinity of optic flow, biomechanics of movement and psychological flow and interaction between these areas which further sets it apart from the existing research.

To answer the research questions, we designed two experiments in which participants were asked to cycle through a virtual environment which was manipulated according to the principles of natural change of optic flow. In the first experiment, participants were exposed to simple textures which allowed for closer comparison with the existing literature in the field. In the second experiment, the spacing between objects matched the first experiment, but simple objects were replaced by more realistic alternatives. Quantitative data on participants' cycling cadence, heart rate, rating of perceived exertion and posture were gathered as well as qualitative data on participants' experiences in form of an exit interview.

2 EXPERIMENT 1

Experiment 1 was designed to be an extension to the studies by Parry et al. [2012], Ludwig et al. [2018] and Baumberger et al. [2000]. The experiment was designed to simulate natural changes of optic flow while cycling through the countryside. Simple optical textures were used in this experiment to allow for a more direct comparison with previous studies such as Ludwig et al. [2018] and Fajen et al. [2005]. Furthermore, this experiment creates a knowledge base and comparison opportunity for Experiment 2 where more complex, natural textures were used. Experiment conditions were designed to further examine Baumberger et al. [2000] suggestion that optic flow on horizontal and vertical surfaces have a different impact on perception.

2.1 Methods

2.1.1 Participants. In total 20 people participated in the experiment. A snowball sampling technique was used for the recruitment. The participant pool was mostly made up out of University of Twente students and staff. Participants were used to frequent cycling as part of their daily lives, but none of them was a professional cyclist. If potential participants were suffering from motion sickness, epilepsy or other conditions that make people prone to (severe) overstimulation and/or seizures, heart conditions, injuries impacting the ability to cycle or balancing issues, they were susceptible to increased risks and were excluded from the experiment. Prior to taking part in the experiment, participants were introduced to the experimental procedure and gave written informed consent. The study was approved by the Computer and Information Science Ethics Committee of EEMCS faculty at the University of Twente, the Netherlands (reference number RP2022-162).

2.1.2 Setup and Apparatus. Experiment 1 was performed at the Human-Media Interaction (HMI) lab on the campus of the University of Twente. Experiment hardware (figure 1) consisted of an exercise bike trainer, a virtual reality (VR) headset, VR capable computer and a chest strap heart rate monitor. Praxtour Course exercise bike was used. It resembles a racing bike and has built-in sensors which provide a real-time data feed of pedal and flywheel momentaneous rotational speed via a USB interface. The pedal rotation speed was used to measure the cyclist's momentaneous work and the flywheel rotation speed was used to measure the actual movement speed of the bike. The bike cycling resistance and the seating position was adjusted at the beginning of the experiment according to the participant's capabilities and wishes. The resistance was set to provide a comfortable and familiar experience for the participant during the experiment. The ideal resistance should be similar to what they were used to while cycling in their daily life. No changes to the bike resistance and bike layout were allowed during the experiment. Participants also did not have access to the gears and a fixed linear relationship between cadence and cycling speed was maintained throughout the experiment.

Fig. 1. Experiment setup.

Valve Index VR headset and Steam VR Base stations 2.0 were used to immerse participants in the virtual environment. This setup gives a good field of view and frame refresh rate. Valve Index allows participants to adjust the distance between the VR headset screens and their eyes to find the most comfortable position. Subsequently, this changes the VR headset's field of view. 90 Hz refresh rate was used even though the headset offered a refresh rate of up to 144 Hz. Via trial and error, it was found that 90 Hz is the optimal setting that worked the best with the available VR-capable computer.

The VR capable computer was equipped with an Intel Core i5-6600 CPU, NVIDIA GeForce GTX1080 GPU and 16 GB of RAM. The hardware was capable of running a virtual environment created in Unity, interfacing with Valve Index VR headset and logging data at the same time.

Polar H10 chest strap heart rate monitor was used to measure the participant's heart rate. It gives continuous heart rate measurement output with an interval of 1 second and also provides the R-R intervals (the interval between two successive heartbeats).

The experiment was recorded with a Panasonic HC-V720 video camera. The recordings had a resolution of 1920x1080 pixels with a 50 Hz frame rate. The camera was set to record the participant from a side (perpendicular to the cycling direction). It was set on a tripod and positioned to capture the whole body of the participant throughout the whole experiment.

The Praxtour bike trainer uses a USB HID communication interface for communication with other devices. A program using Python programming language was made to interface with the bike. It captured real-time data and also allowed the adjustment of cycling resistance. This program also received data on the momentaneous virtual environment texture condition and the rating of perceived exertion (the researcher entered the participant's current rating of perceived exertion during the experiment via an input field in the Unity environment immediately after the participant verbally gave an answer). Python program and Unity program communication happened via a web socket. All this data was logged in a comma-separated values (CSV) file with a frequency of 50 Hz.

The virtual environment was built in Unity. An endless road game generation principle was applied to iteratively create a cycling road. The initial road was made from seven tiles with the same texture (figure 2 shows a single tile). The optimal number of tiles was found via trial and error. A race bike model resembling the Praxtour Course bike trainer was placed in the virtual environment on the first tail of the endless road. The velocity of the bike in virtual reality was proportional to the bike trainer's flywheel speed and updated with a frequency of 50 Hz. As the participant moved forwards, a new tile was spawned at the end of the currently displayed tiles every time participants exited a tile. The tiles behind the participant were deleted to maintain performance over time.

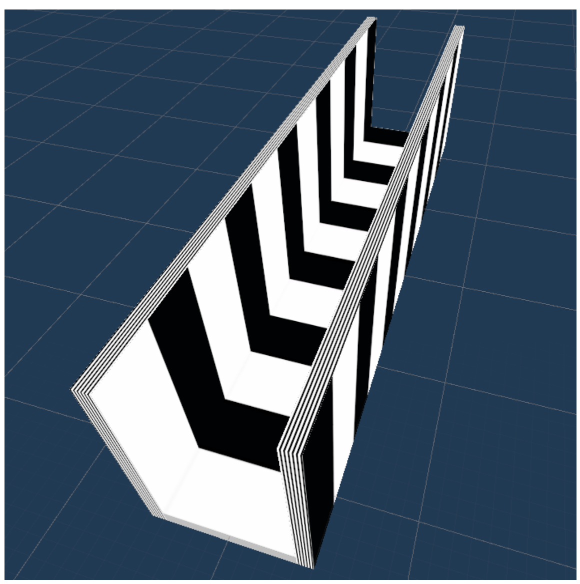

Fig. 2. Image of a simple texture tile.

Participants could change their seating posture and grab the race bike's steering wheel in a wide variety of ways during the experiment. We did not have the means to accurately track participants' hand position and posture in real-time, thus a decision was made to not use an avatar and avoid the feeling of mismatch between participant's posture in real-life and virtual reality. The race bike model represented real-time real-life participants' actions in virtual reality and was deemed sufficient to link action with perception. Participants' viewpoint in virtual reality was set in a way that resembles sitting on a race bike. Furthermore, the wheels of the bike model were rotated proportionally to the Praxtour bike's flywheel speed to create a more immersive experience.

2.1.3 Design. During the experiment, participants were asked to cycle on a bike trainer while wearing a virtual reality headset and being placed in the virtual reality environment. They were instructed to cycle in a similar fashion as cycling to the university or work - consistent cycling with a goal in mind, *"You have a destination in mind and you want to reach it. Think about how you are cycling to university/work when you have a meeting in a bit. You are currently not late, but you also want to be there on time so you make steady progress to reach the destination.*". The comfortable cycling speed gave participants room for speed increase and decrease, while the "cycling with a goal in mind" approach was meant to promote relatively consistent approach throughout the experiment.

The optic textures were placed on three surfaces in the participant's field of view - the floor and two walls, one on each side of the participant. Black rectangles on a white background were used to introduce edges on surfaces in the field of view. Trees passing by a cyclist in a natural environment were seen as the inspiration for this shape. We maximally simplified the shape of a tree and arrived at a vertical two-dimensional rectangle. To allow for direct comparison between vertical and horizontal surfaces, the rectangles with the same dimensions were placed both on the floor and the walls. Above the walls, a blue sky was displayed.

Four unique tiles with specific optic textures were used - a) containing no clear edges on the walls and the floor (empty condition), b) edges only on the floor (textured floor condition), c) edges only on the walls (textured walls condition) and d) edges on the walls and the floor (full condition). In the textured conditions, the rectangles were periodically repeated on the surface. The same repetition frequency was used in all conditions and on all surfaces.

Each participant experienced four transitions to different textures and saw all four unique conditions in random order. The time spent in the first condition until the first transition was considered to be a warm-up period and data from this time was not included in the dataset. The first texture condition was shown once more as the last one and data generated during this time was included in the dataset. Participants were kept in each experimental condition for a minimum of 120 seconds. After 120 seconds had passed and once the participant exited the current tile, condition change was initiated and a tile with a new condition was spawned at the end of the endless road. This approach replicates the scenery change in real life. First, we see the new scenery in the distance and gradually move towards it until we are surrounded by the new environment. At the end of the experiment, a banner was shown in the virtual environment to inform the participants about the end of the experiment and thank them for their participation.

Due to the experiment design, the time spent in each condition varied slightly. If the 120 second timer expired when a participant was at the end of a tile, the transition was triggered earlier compared to a situation when a participant was at the beginning of a tile. Transitions between conditions were distance-based (length of 7 road tiles), thus the time spent in a transition was fully proportional to the participant's cycling speed.

The valid data which were afterwards analysed covered 4 transitions and 4 conditions for each participant. On average, the period of valid experiment data per participant was around 10 minutes (influenced by the participant's cycling speed). During the experiment, the participant's pedalling speed, heart rate and the bike's flywheel speed were constantly measured. A video was captured of the experiment from which skeletal key points as well as their position change over time could be extracted. Periodically, at predetermined moments during the experiment, participants were asked to give their current rating of perceived exertion (RPE) using the Borg Category Ratio Scale (CR10) [Zamunér et al. 2011]. The CR10 scale has a range of 0-10 where 0 represent no effort and 10 is associated with maximum effort.

First they were asked to estimate their current RPE 20 seconds after entering a condition was used to estimate the effect of the transient effect (occurring during and immediately after the transition). Participants were asked to rate their RPE again 90 seconds after entering a condition to estimate the RPE associated with the persistent effect of the specific texture condition. An exit interview was carried out at the end of the experiment. All of this data constitutes the dataset obtained during this study.

The timing of the RPE measurements during the experiment was approximate due to the way it was measured. The researcher asked participants to rate their rating of perceived exertion at predetermined times, but the time between the question and the answer was dependent on the participant. Sometimes participants responded immediately, sometimes they took some time to think about their answer.

2.1.4 Data Analysis. Literature suggests that the rating of perceived exertion increases over time during an activity [Parry et al. 2012; Parry and Micklewright 2014], thus first the global trends in the data were assessed. This was done to the rating of perceived exertion, heart rate and cycling cadence. First, the change of the mean values associated with each texture condition and transition relative to the first transition was calculated within the participant. Afterwards, this data was used to calculate the change and standard deviation of the whole data set.

The optic texture effect on performance was evaluated by comparing cycling cadence in each texture condition. First, the mean cycling cadence per texture condition was calculated within participant and afterwards, the data were combined in a dataset (n=20). Mean cadence distribution per condition was tested for normality (Shapiro-Wilks test) and afterwards appropriate statistical test (one-sided paired t-test for normally distributed data or Wilcoxon signed-rank test for non-normally distributed data) were used to compare means and test the effect. The size of the data set (n=20) was not large enough to be able to apply the central limit theorem. A confidence level of 95% was used in all statistical tests carried out during this study.

Increasing pedalling cadence over time was a trend that was not initially expected. The pedalling cadence data were detrended within participants by subtracting the linear best fit line. The data was further standardised by calculating within participant z-scores. Shapiro-Wilks test was applied to test for normality. A one-sided paired t-test was used to compare the means of normally distributed data and the Wilcoxon signed-rank test for non-normally distributed data.

The previous analysis was done with an underlying assumption that each texture condition has an effect that carries through the whole experiment. This might not necessarily be the case, thus pairs of conditions following each other were also compared. The mean pedalling speed and detrended mean pedalling speed of the following texture relative to the values from the preceding texture were plotted. This was done separately for each following texture pair within each participant.

Furthermore, confirmatory mixed model analysis was done to validate the results of the previous tests. During the experiment, texture conditions were shown in random order and previously unexpected cycling speed increase over time was observed. Furthermore, in previous analysis we worked under assumption that specific conditions have an absolute effect on cycling cadence and perceived effort, but it is also possible that this effect is relative to the previous condition. Lastly, exit interviews and observations in data suggest that there might be individual specific factors influencing participant behaviour. Mixed model analysis was constructed to account for these assumptions and observations. Mean cycling speed at each texture condition was seen as the dependant variable which were influenced by three fixed factors: current texture condition, previous texture condition and the time slot at which specific texture condition was shown during the experiment. Participant ID was used as a random factor to account for individual differences between participants.

Qualitative data was gathered during the exit interview to evaluate the participant's perceived performance in each condition. The participants were asked if they felt any performance differences between textures and if they did, which felt the fastest and which felt the slowest. These results were plotted as a bar graph. Some participants said that multiple conditions felt the fastest or the slowest, thus the total amount of answers in the bar graphs is larger than the number of participants.

The second research question focuses on the effect optic flow has on perceived exertion. Heart rate has been considered a measure of actual effort and rate of perceived exertion is a measure of perceived effort. It is expected that both measures would increase in overtime and track each other. Discrepancies in the trend could be caused by changes in optic flow. We looked for the most extreme cases of discrepancies between both metrics - when one increased and the other decreased. Both measures were plotted side by side per participant to check this assumption and afterwards, the discrepancies between both measures were visually identified.

During the exit interview participants were asked if they felt differences in the demandingness of different optic flow conditions. If they felt differences in the demand, they were also asked to tell which was the most and the least demanding texture. The results were summarised and displayed in a bar plot. Some participants found more than one texture to be similarly demanding, thus the sum of all answers in the bar plot is larger than the number of participants per experiment (n=20).

2.2 Results

The average rating of perceived exertion (RPE) increased over time (figure 3). When examining results on an individual scale, an increasing perceived effort over time can be observed in the data of 15 participants. In the case of the other 5 participants, RPE stayed constant or went down at some point during the experiment. Figure 3 also shows participants' heart rate increases over time. The participants' mean heart rate in the last condition was 1.09 times higher *(SD=0.062, MIN=0.96, MAX=1.22)* than the average heart rate during the first condition.

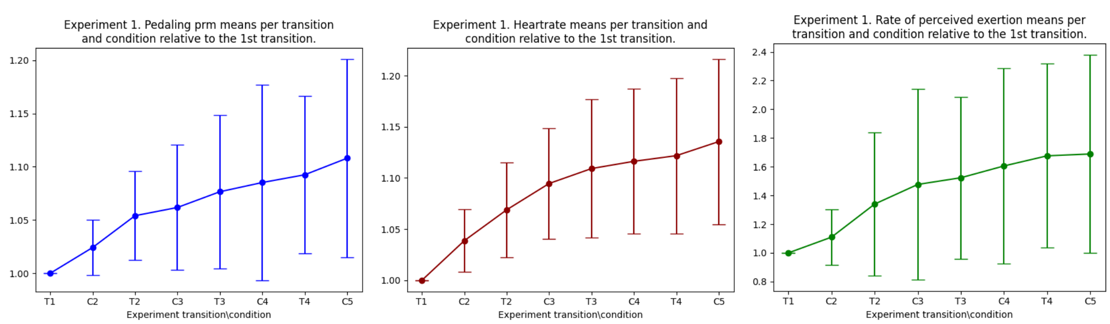

Fig. 3. Mean pedalling cadence, heart rate and rating of perceived exertion per condition and per transition during Experiment 1.

The trend of increase over time can also be seen when looking at the mean pedalling cadence per transition and condition throughout the experiment (figure 3). When compared to the first transition, the mean pedalling cadence during the fourth transition is 1.10 times higher *(SD=0.074, MIN=1.00, MAX=1.26)*.

After the global trends in the data were observed, we looked at the mean pedalling cadence associated with each optical texture condition. During the first experiment, the mean pedalling speed in the empty condition was 66.29 rpm *(SD=15.42)* and 65.95 rpm *(SD=13.83)* in full condition. A one-sided paired t-test resulted in *(p-value of 0.33)* which indicated that the mean pedalling speed was not significantly lower in the texture condition with a higher edge rate. The mean pedalling cadence between the textured floor condition and the textured walls condition were compared next. The mean pedalling cadence was 65.82 rpm *(SD=15.41)* for the textured floor condition and 66.04 rpm *(SD=15.99)* for the textured walls condition. Since the pedalling cadence data points from this experiment were not normally distributed, Wilcoxon signed-rank test was used to compare the means. The p-value of 0.81 indicated that these means are not significantly different.

The same tests were carried out on the detrended and standardised pedalling cadence data. Detrended pedalling speed z-scores mean in empty texture condition was on average -0.17 *(SD=0.56)* standard deviations below the participant's average cycling cadence during the experiment. In the full texture condition, this value was 0.015 *(SD=0.47)* above the average cycling cadence. A one-sided paired t-test resulted in a p-value of 0.19 and thus, there is no significant difference between these means. Next, we assessed the pedalling cadence means for the textured floor and the textured walls conditions. The detrended pedalling cadence z-scores mean was *(MEAN=0.11, SD=0.35* for the condition with textured floor as opposed to *MEAN=0.049, SD=0.35)*, but this difference was not significant according to the one-sided paired t-test *(p=0.33)*.

The mixed model analysis confirmed previous observations. Experiment time slot had significant effect on the cycling cadence *(p<0.001)*, but current texture condition, previous texture condition and their interaction did not have significant effect on cycling cadence.

In the exit interview, the participants were asked in which textures they perceived their movement speed to be the fastest and in which the slowest. After Experiment 1, the pedalling speed in the full texture condition was considered to be the fastest by most participants (9 answers) and the participants felt it was the slowest in the empty condition (7 answers). 8 participants indicated that there was no clear fastest or slowest condition.

Overall heart rate and rating of perceived exertion match each other, but there are some differences. By looking at the differences and discrepancies between both measurements it is possible to find under which conditions mismatches between a person's actual exertion and perceived exertion occur. 6 participants reported that their rating of perceived exertion was lower following a transition between experimental conditions and 1 participant indicated that a reduction in RPE occurred after spending 90 seconds in empty and textured floor conditions.

During the exit interviews, participants were asked if they experienced demand differently in different experimental conditions. The empty condition was considered to be the most demanding by half of the participants in Experiment 1. The second most selected texture was the full condition with 6 answers. When asked for a texture that felt the least demanding, participant answers showed no clear trend as all texture conditions were mentioned an equal number of times (7).

Pedalling speed in a condition relative to the previous condition was plotted and visually analysed. No clear general trends could be observed in the data from Experiment 1. That said, it can be seen that pedalling speed in a textured floor increased if it followed full texture condition.

2.3 Discussion

The observed increase in the rating of perceived exertion and heart rate is in line with the literature and observations of other studies. However, the overtime increase in pedalling cadence is an observation that was not expected. The participants were asked to purposefully cycle to a goal and they had 2 minutes in the first unrecorded condition to settle into this routine. Nevertheless, a steady increase in pace occurred. During the exit interviews, participants talked about the boredom and monotony experienced during the study. They spent 120 seconds in each condition, but it was enough for participants to get accustomed to this simple environment. Some participants talked about an urge to speed up to reach the next condition sooner and see something new.

No significant difference was found between mean cycling cadence in different conditions. In previous research, usually a small, but significant difference has been observed. It could be argued that the gradual and significant cadence increase over time has obstructed these differences in our study.

While the quantitative data analysis techniques showed no significant differences between cycling cadence in different textures, the participants experienced perception differences according to the exit interview. The largest part of the participants felt that they cycled the fastest in the full texture condition and the slowest in the empty conditions, which is in line with the previous research [Baumberger et al. 2000; Parry et al. 2012]. There were participants who indicated that other conditions were the fastest or the slowest. Furthermore, a large part of the participants did not feel noticeable differences between different textures. It was expected that the perceived higher cycling cadence would result in a lower actual cycling cadence and vice versa. The differences in perception could indicate the existence of other factors that have an impact on the way how a person perceives and reacts to specific optic flow.

According to the literature [Parry et al. 2012], we should observe a gradual increase in the rating of perceived exertion (RPE) over time and the decreases of RPE are not usual observations. While only one person experienced a decrease in RPE after spending 90 seconds in a condition, 6 people (30% of participants) reported a decrease after a transition between texture conditions. During the exit interview, participants mentioned that they were looking forward to transitions as the conditions got monotonous and boring at some point. While topics such as motivation and engagement are out of the scope of this study, the results of this experiment suggest that optic flow has some effect on them.

Exit interview answers show that empty conditions were deemed to be the most demanding by half of the participants. The empty condition did not feature any clear edges and provide information about persons' movement speed, thus it was difficult for the participants to accurately judge their cycling speed. The largest group of participants also considered their cycling speed to be the slowest in the empty condition due to this. That said, there was a participant who said the exact opposite *"I felt like I was cycling at the speed of light in the empty condition"*.

3 EXPERIMENT 2

Experiment 2 was designed to be an extension of Experiment 1. Simplified textures were replaced by more realistic alternatives, but their spacing and other aspects of the experiment were kept the same to allow for between-experiment comparison.

3.1 Methods

3.1.1 Participants. In total 20 people participated in the second experiment and they were recruited using the snowball sampling technique. Participants for this experiment had the same profile as in Experiment 1 and also the same exclusion criteria were used. There were no participants who participated in both experiments. All participants were introduced to the experimental procedure before the start of the experiment and gave written informed consent. Experiment 2 was approved by the Computer and Information Science Ethics Committee of EEMCS faculty at the University of Twente, the Netherlands (reference number RP2022-162).

3.1.2 Setup and Apparatus. During Experiment 2 the same experimental setup was used as in Experiment 1 (see section 2.1.2) and we also followed the same procedure. Only the textures that were displayed on the walls and floors of the virtual environment were different between these experiments. A tile used in Experiment 2 can be seen in figure 4.

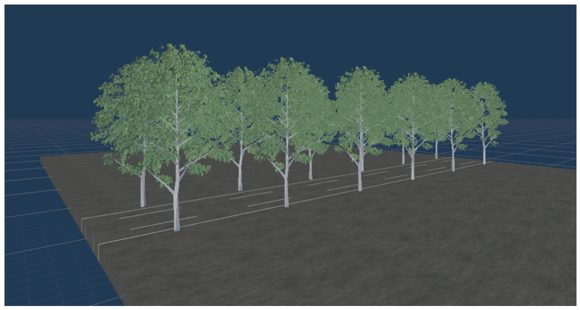

Fig. 4. Image of a complex texture tile.

3.2 Design

Experiment 2 was carried out following the procedure of Experiment 1 with the exception of used textures. The textures in Experiment 1 were simplified versions of the shapes present in Experiment 2 which resembled a real-world environment with an asphalt road in the middle of the scene and periodically placed trees on both sides of the road (instead of the white walls with black rectangles). The trees and lines were placed in Experiment 2 with the same interval as the rectangles in Experiment 1. Since the trees were three-dimensional, they were centred with two-dimensional walls and rectangles. A single tree model was used to create trees. This was done to avoid variance in tree size and overall shape. To increase the variety and make sure that the environment looks more realistic, trees standing next to each other were slightly rotated so the participant would see the model from a different angle. The other dimensions of the trees stayed the same. The stripes on the asphalt were aligned with the trees and had the same length as the width of the widest part of the tree and rectangles used in Experiment 1. Thus, the edge rate *(Edge rate (ER) [Fajen 2005; Larish and Flach 1990; Warren 1982] is described in the number of objects passing a fixed reference point in units of time)* was kept the same in both experiments, but the surface optical density *(Surface optical density (SOD) is defined by the authors of this study as an extension of global optical density [1982] and is the distance to surface divided by surface texture element size)* was higher in the second experiment due to the level of detail in the natural textures.

3.2.1 Data Analysis. The results of the second experiment were analysed following the same procedure as Experiment 1 described in section 2.1.4.

3.3 Results

The global trends in the data of Experiment 2 were in line with the global trends of Experiment 1 shown in the figure 3. The mean pedalling cadence in the empty condition was 67.46 rpm *(SD=12.26)* and 66.12 rpm *(SD=12.36)* in full condition. A one-sided paired t-test resulted in a p-value of 0.087 which can be seen as a marginally significant. The detrended pedalling cadence z-scores mean in empty texture condition was 0.040 *(SD=0.45)* and -0.15 *(SD=0.29)* in the full condition. However, the one-sided paired t-test *(p=0.088)* also showed only marginally significant difference between the means.

The mean pedalling cadence in the textured walls condition was 67.73 rpm *(SD=11.96)* and 66.84 rpm *(SD=12.28)* in the textured floor condition. This difference was not statically significant according to the one-sided paired t-test *(p=0.14)*. Afterwards, the detrended z-values were assessed in the same way. The mean value in the textured walls condition was 0.061 *(SD=0.46)* and the mean value in the textured floor condition was 0.044 *(SD=0.47)*. The p-value of paired one-sided t-test was 0.46, thus both means are not significantly different. Bar charts with pedalling cadence means per texture and per experiment can be seen in figure 5.

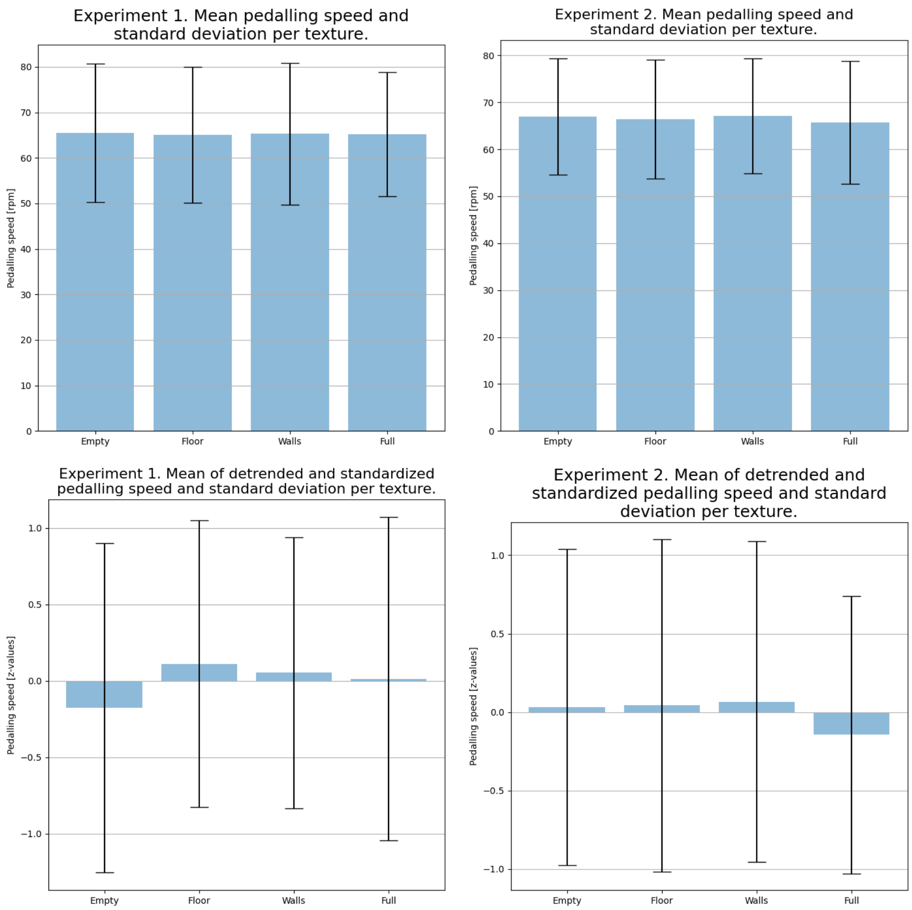

Fig. 5. Mean pedalling speed and detrended pedalling speed z-scores per texture condition.

The mixed model analysis confirmed the previously mentioned results also for Experiment 2. Experiment time slot had significant effect on the mean cycling cadence *(p<0.001)*, but current texture condition, previous texture condition and their interaction did not have significant effect on cycling cadence.

Participants' answers during the exit interview on the condition with the fastest and the slowest perceived cycling speed are summarised in figure 6. Some participants said that more than one condition felt the fastest, thus the sum of all answers is larger than the number of participants in each experiment. When looking at Experiment 2, the pedalling speed in the empty condition was considered to be the fastest by most participants (7 answers). The results for the slowest perceived texture are less clear and do not show a clear front runner. Textured walls and empty condition were both mentioned 4 times. 8 people could not point out the fastest perceived texture and 7 participants could not point out the slowest perceived texture.

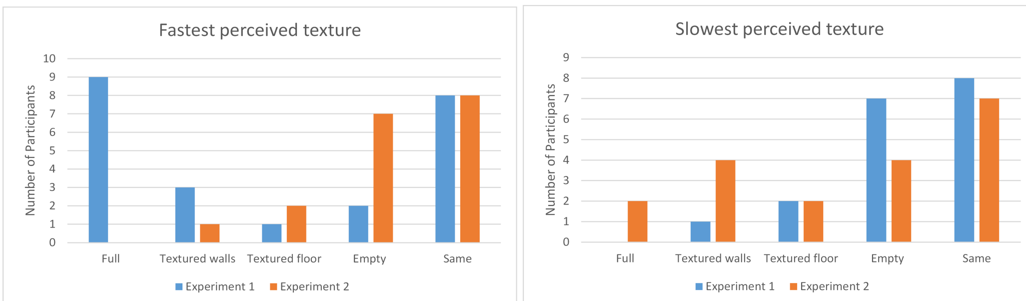

Fig. 6. Perceived cycling speed according to the exit interview.

During the second experiment, a reduction in the rating of perceived exertion after a transition could be observed for 45% of the participants (9 out of 20). 5 participants indicated lower perceived exertion after spending 90 seconds in a condition. This also occurred in the empty and textured floor conditions which were the same as in Experiment 1.

Participants perceived demandingness of each experiment condition according to the exit interview is summarised in figure 7. The empty texture condition was also considered to be the most demanding by most participants (8 people) in the second experiment. Considerably fewer participants picked other answers for this question. When asked to identify the most demanding condition, the results were close with full (7 answers) and textured walls (6 answers) conditions in the lead.

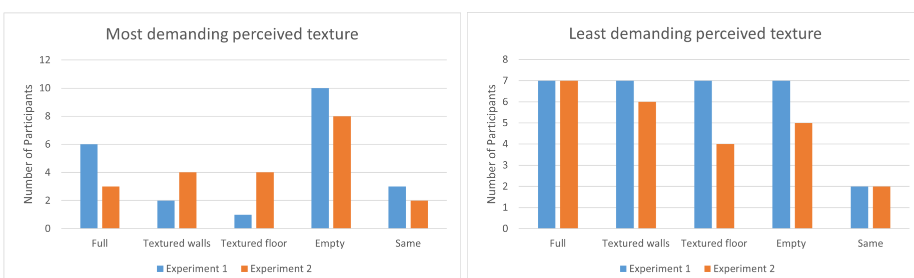

Fig. 7. Perceived demandingness of textures according to the exit interview.

Pedalling cadence change was also assessed between two following conditions. In Experiment 2, participants' mean pedalling speed was always higher in the empty condition irrespective of the texture of the previous condition. The opposite effect was observed for the full texture condition.

3.4 Discussion

Similarly to Experiment 1, also during Experiment 2 an over time increase in rating of perceived exertion, heart rate and pedalling cadence was observed. Furthermore, no significant difference between mean pedalling cadence in different conditions was found.

During the exit interview, most participants mentioned that their cycling cadence in empty condition felt the fastest. This observation is opposite to Experiment 1 where the full condition was perceived to be the fastest. Furthermore, this observation is also not in line with literature findings [Denton 1980; Parry and Micklewright 2014] where a higher edge rate is associated with higher movement speed. The type of textures was the only difference introduced between both experiment and thus could be a cause of these perception differences. The spacing between objects in the second experiments was kept the same, but the surface optical density was increased due to the use of natural textures. The exit interview results suggest that simple and complex textures and environments are perceived differently.

45% of participants (15% more than in Experiment 1) reported a reduction in the rating of perceived exertion after a transition to a different condition. The observation suggests that perceived exertion is lower during a changing environment compared to a monotonous one. An increased number of participants (5 as opposed to 1 in Experiment 1) also reported lower perceived exertion after spending time in empty and textured floor conditions. The textures in which the effect occurred are in line with Experiment 1 and suggest that textures on horizontal and vertical surfaces are indeed perceived differently as per Baumberger et al. [2000].

3.5 General discussion

No significant differences in pedalling cadence were found between texture conditions in both experiments. It is possible that the smaller changes in cycling cadence were obstructed by the overtime increase in cycling speed. An attempt was made to detrend the data by subtracting the linear best fit line, but it is possible that the linear best fit line does not fully describe this trend and does not fully cancel it out. Mixed model analysis was done on the mean cadence speed per condition which further confirmed that the time slot had significant effect on the mean cadence speed, but previous texture condition, current texture condition and their interaction did not have significant effect on the means. The time series data can be analysed with more complex statistical methods such as General Additive Mixed Modelling (GAMM) to obtain more detailed insights. Preliminary GAMM analysis of the dataset (which is out of the scope of this study) showed an effect of optic flow on cadence. Preliminary results show that participants' cadence was the fastest in the empty condition, followed by full condition and textured wall condition with a similar slower cadence came and the slowest cadence was associated with the textured floor condition. The preliminary results of GAMM are in line with previous studies on optic flow. Higher edge rate and global optic flow rate are usually associated with lower actual cycling speed which is in line with the preliminary results. Furthermore, Baumberger et al. [2000] suggest that optic flow on horizontal surfaces has more impact than optic flow on vertical surfaces. If this holds, the textured floor condition should be perceived similarly to the full condition and the textured floor condition should be perceived similarly to the empty condition. In the preliminary results of GAMM, cadence is faster in the empty condition compared to the full condition and it is also faster in the textured walls condition compared to the floor condition. Thus, the preliminary results are in line with Baumbeger et al. [2000]. Further data analysis using GAMM or any other advanced data analysis technique was out of the scope of this project, but can be done as a follow-up study with the gathered dataset.

While there was no significant difference in pedalling cadence between texture conditions, participants reported perceived speed differences between textures in the exit interview. The differences between experiments have to be highlighted. In Experiment 1, most participants (9 out of 20) found the full condition to be the fastest which is in line with the previous research findings [Denton 1980; Fajen 2021; Mohler et al. 2007; Parry et al. 2012]. Exit interview of Experiment 2, however, had opposite results and the empty condition (7 out of 20) was perceived to be the fastest. Even more, only two people mentioned the empty condition to be the fastest in Experiment 1 and no one perceived the movement speed to be the fastest in the full condition in Experiment 2. Full and empty conditions were designed to be the polar opposites - many clear edges all over the field of view versus no clear edges anywhere in the field of view. Texture conditions in both experiments were designed following the same principles with the surface texture density of used textures being the only difference. The perception differences between both experiments suggest differences in the perception of simple and complex textures. Participants talked about feeling overwhelmed, stressed, peaceful and bored in some textures. There was no clear link between these factors and specific textures which suggests that there are also some individual factors impacting perception.

In both experiments, a reduction in the rating of perceived exertion (RPE) was observed after the transition. This was not a universally applicable finding but could be seen in the data for 30% of participants in Experiment 1 and 45% in Experiment 2. Some participants elaborated on this change during the exit interview. Participants said that they were looking forward to transitions and seeing new textures as they brought something new and exciting. Motivation and engagement are outside of the scope of the study, but the results of the study suggest a connection between these concepts and optic flow. We also observed a reduction of RPE for a few participants in the empty and textured floor condition in both experiments. While the reduction in the rating of perceived exertion was observed in the empty condition, it was rated to be the most demanding by most people in both experiments. Participants said that the empty conditions lacked hard edges which made it harder to perceive the speed of motion. That said, the asphalt texture in Experiment 2 was seen as a large improvement over the emptiness of Experiment 1 and participants were able to judge their movement speed better.

During exit interviews, participants talked about the intensity of optic flow and its impact on them. Some people found the empty condition boring while for some it felt relaxing compared to the other textures. Some people found trees in Experiment 2 interesting and engaging - *"I felt like cycling on a rural road looking around at the trees and trying to see all the detail"*, while for others they felt overwhelming. The experiment also highlighted the power of associations. One participant said that the black rectangles on the walls in Experiment 1 reminded him of building in the city. The participant felt the same during the experiment as the corresponding texture conditions were more stress full. Literature has shown that optic flow has an impact on motor control [Fajen 2005; Postma et al. 2017; Warren et al. 2001]. That said, the comments of participants suggest that there is a variety of factors specific to each individual that influence how each individual perceives this effect.

During the initial data analysis, we only looked at the most extreme case of deviations between heart rate and RPE (when one went up and the other went down). Literature tells that exertion increases over time during an activity even when the actual intensity of the activity did not increase, but the slope of this increase can vary [Parry et al. 2012]. With the use of more advanced analysis techniques (such as GAMM), it would be possible to assess the relative rate of increase of heart rate and RPE in different texture conditions and find out if there are significant differences in the slope of this increase.

4 CONCLUSION

The study aimed to answer two research questions: *1) How do changes in optic flow density impact the biometric parameter of cycling cadence? 2) How do natural changes of optic flow impact how we perceive effort?* During the study, no significant effect of natural changes of optic flow on cadence was found. A gradual and significant increase in cadence over time was observed independent of the order of texture conditions. During this study we did not uncover the cause of this phenomena, but it can be a focus of a future study. In exit interviews participants mentioned boredom, motivation and excitement might could be linked with the gradual increase of cycling cadence.

Participants perceived differences in cycling speed in different textures according to the exit interview. We also saw perception differences between experiments. For example, when asked to identify the texture condition with the fastest perceived cycling speed, the full condition was mentioned the most by the participants of Experiment 1 and the empty condition was mentioned the most by the participants of Experiment 2. The exit interview findings suggest that the type of texture and its surface optical density has an impact on the way it is perceived. Furthermore, the data suggest perception differences that are caused by factors specific to each individual. We found signs that natural changes of optic flow affected the perception of effort. A group of participants reported a reduction in the rating of perceived exertion after a transition to a different condition. Furthermore, some participants also experienced a reduction in perceived effort after spending time in empty and full conditions. This experimental data was further supported by the exit interviews were participants where asked to identify the most and the least demanding textures. The empty condition was seen as the most demanding by most participants (10 out of 20 in Experiment 1 and 8 out of 20 in Experiment 2) in both participants. The findings are in line with the previous research, but it also has to be pointed out that a relatively large part of the participants gave different answers and these results suggest the impact of factors specific to each individual. Further analysis of the obtained dataset has to be carried out with more complex analysis techniques to further support the initial findings and gain new insights.

The research project was expected to give three main contributions to the field of optical flow - the creation of a VR setup that allows for perception-action research on optic flow, a dataset for explorative research on the effects of natural changes of optic flow on the biomechanics of movement and the psychological flow and preliminary analysis of the said dataset. These goals have been achieved at the end of this study.

ACKNOWLEDGMENTS

First, I want to thank my supervisor Dees Postma and Dennis Reidsma for making this study possible! Thank you, Dees for our weekly meetings and guidance that led me through the project. I always enjoyed our conversations! Next, I want to thank all the experiment participants. Without you, none of this would be possible. Thank you for your time, interest and effort! Daniel, thank you for a place in the interaction lab, helping with equipment and experiment place! You made sure I felt welcomed at the Interaction Lab and had everything necessary to succeed. Thank you Alfred for making the Praxtour bike available for the study. Thank you Tom for sharing your experience and knowledge on Praxtour bike, VR study design and ethics forms. I want to thank all my friends who were there for me throughout the thesis! Especially big thank you goes to Jordi who was also my working buddy and coffee buddy and was always willing to help with ideas and practical matters! Last but not least, I want to thank my family and Sarah! Thank you for being there for me through this whole journey. I could not have done this without you!

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