A VR cycling study on visual attention allocation and subjective risk perception at intersections

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ABSTRACT

Cyclists need to constantly scan their surroundings for potential hazards. This is particularly true for intersections with cars approaching from different directions. Our knowledge about how cyclists allocate their visual attention towards certain directions (or not) is so far limited. We designed a virtual intersection that participants crossed in several variations on a virtual bike while wearing a head mounted display. We hypothesized that the visual accessibility of intersection branches affect the attention towards the respective direction as well as the attribution of risk are perceived as less dangerous than areas of medium visual accessibility. We found that subjective risk perception differed significantly between the street branches, independent of the travelling direction, as well as depending on the way the intersection had to be crossed (e.g. a sharp turn increased the hazard estimate in general). Contrasting our expectations, we found no evidence that the spatial position of an intersection branch in relation to the traveling direction affected the participant’s hazard estimate. In other words, intersection branches located more to the right or left were not rated more dangerous, although it should be more difficult to spot cars approaching from these directions. We discuss our experiences with VR studies as a method for studying cycling safety and outline a subsequent study addressing the identified issues.

Keywords: virtual reality, subjective risk perception, intersections
1 INTRODUCTION

Cyclists as a group of vulnerable road users need to constantly scan their environment for potential hazards, particularly when riding in urban areas. Thus, it seems highly important to understand cyclists’ hazard perception (Melin et al., 2018; van Paridon et al., 2021). There are recent findings showing that the spatial configuration of the local environment affects both the experience of subjective safety as well as the allocation of visual attention towards specific locations (von Stülpnagel, 2020; von Stülpnagel & Schmid, 2019). A particularly relevant scenario in this regard are intersections, which have been found to impose an increased risk for cyclists (e.g. Vandenbulcke et al., 2014; von Stülpnagel & Lucas, 2020). However, there appears to be little research on how the position of an intersection branch relative to a cyclist’s travel direction affects the attribution of risk and attention towards this direction.

The high number of uncontrollable variables limits real world investigations on this matter: the existing layout of the urban environment cannot easily be adjusted to a researcher’s needs, while the volume and behavior of other road users is mostly unpredictable. Virtual reality (VR) represents a potential solution to these challenges, which has gained traction among researchers investigating cycling safety.

1.1 Virtual reality as a tool in cycling safety research

VR setups provide distinct advantages over other approaches, for example the almost complete control over the experimental conditions as well as the physical safety of the participants in otherwise dangerous situations. Several studies used video clips to investigate how factors such as cycling experience affect hazard detection rates and subjective risk perception (e.g. Lehtonen et al., 2016; Vansteenkiste et al., 2016). Despite several merits of this presentation format (e.g. the complexity of the real-world situation), the presentation of the displayed scene is bound to a specific point of view, without any degree of freedom for the participant.
The use of head mounted displays (HMD) provides a tool enhancing the possibilities in this regard, as they allow participants to look around in a natural fashion. 360° images have been successfully used to present specific locations and evaluate the level of subjective safety with cycling at specific locations (e.g. von Stülpnagel & Krukar, 2018; von Stülpnagel & Schmid, 2019). This approach can be further extended to the presentation of 360° videos (Liu et al., 2020). The experience and behavior of participants wearing HMDs in cycling studies has been found sufficiently close to cycling in the real world (e.g. Abadi et al., 2019; Nazemi et al., 2019). Despite the enhanced degree of freedom provided by HMDs concerning the viewing orientation, they are still limited in some regards. When presenting recorded images or videos, participants are fixed to the location of the recording, as the system cannot account for vertical, lateral, or horizontal movements of the participant. This may increase the risk of cyber sickness and decrease the level of immersion. This shortcoming can be overcome by head tracking (e.g. van Paridon et al., 2021) or other presentation formats such as stereoscopic videos (e.g. Tang et al., 2007). However, this also requires a virtual model of the environment rather than a simple recording, thus increasing the costs of creating a convincing VR environment.

1.2 Eye tracking in cycling safety research

Several studies highlighted the potential of gaze behavior as a way to analyze cyclists’ behavior and perception. In a study by van Paridon and colleagues (2019), a high distraction scenario resulted in a reduction of the time young cyclists attended to the direction of travel (i.e. a higher level of gaze entropy). Trefzger, Blascheck, Raschke, Hausmann, & Schlegel (2018) used a category system to cluster fixations on, for example, the path, pedestrians, or advertisements, in order to understand the gaze focus of cyclists. Closer to the aims of the present research, Rupi and Krizek (2019) analyzed the gaze behavior of cyclists at different types of intersections in a real-world setting. They report longer fixations times at intersections where participants cycled
on the road (and thus felt potentially more at risk) as compared to intersections with a cycling track. Additionally, more (as compared to less) experienced cyclists showed longer fixation durations. Finally, the authors hypothesize on more active search strategies, particularly for inexperienced cyclists. Von Stülpnagel (2020) aimed at linking the location a cyclist looks at (i.e. the location normally investigated in eye tracking research) and the body location the cyclists looks from. This sight vector’s length (first introduced by Müller-Feldmeth et al., 2014) provided insights into how cyclists scan their environment for obstacles and hazards. Further information was derived from the gaze angle, which indicates the extent to which the gaze deviates from the current direction of travel (Schwarzkopf et al., 2017): Spatially more complex locations resulted in larger gaze angles.

The annotation and extraction of eye tracking data is a mostly manual and thus highly time-consuming process. Recent technological developments have enabled the integration of eye tracking technology in VR setups (e.g. Bauer et al., 2018), which promises to greatly simplify the data preparation. HMDs with integrated eye tracking technology are now commercially available, but their application is as of yet not widespread in academic research. One of the few studies featuring such technology found comparable (gaze) behavior when comparing cycling at real locations and their virtual counterparts (van Paridon et al., 2021).

Even without a dedicated eye tracking system, the HMD’s sensors already provide highly accurate data about the orientation of its wearer’s head. Additionally, the horizontal field of view (FoV) of the most established HMDs covers about 90°, forcing it’s wearer to orient the head more actively towards the object of interest. It might thus be worthwhile to investigate whether this orientation can provide information about a person’s visual attention allocation.
1.3 Risk attribution and visual attention towards intersection branches

Intersections have been found to impose an increased risk for cyclists (e.g. Vandenbulcke et al., 2014; von Stülpnagel & Lucas, 2020). We argue that a cyclists’ allocation of visual attention towards a street at an intersection as well as the level of subjective risk perception attributed to this street is affected by its spatial position and visual accessibility. More specifically, we expect that an intersection branch in front of a cyclist is visually accessible and thus perceived as manageable and less dangerous. Intersection branches located more to the left and right to the cyclist’s travel direction are visually less accessible, and may thus be perceived as less controllable and more dangerous. To our knowledge, there is as of yet no systematic approach on this matter.

The aims of this research are thus three-fold. First, we aim at creating a simple but immersive VR setup that allows us to study subjective risk perception of cyclists crossing an intersection. Second, we hypothesize that visually more accessible intersection branches (e.g. those located more in front of the cyclist) are perceived as less dangerous. Third, we want to examine whether the head orientation as measured through the orientation of a head-mounted display can provide insights into the visual focus of participants.

2 METHOD

2.1 Participants

Participants were undergraduates of the University of Freiburg and reimbursed with course credit. They were required to have normal or corrected-to-normal vision by contact lenses because glasses were incompatible with the head-mounted display (see Section 2.2.2). Four participants did not complete the study due to cyber sickness syndromes. Their data were excluded from all analyses reported below. Data of 20 participants (13 of them females; age
ranging from 18 to 29 years, $M = 21.15$, $SD = 2.80$; most of them students; 18 reporting German to be their native language) remained for further analysis.

2.2 Materials

2.2.1 Creation of the virtual environment

We created a virtual model inspired by a real-world intersection with the Unity game engine. Three of the intersection branches were streets accessible for motorized vehicles and cyclists; one intersection branch leading into an underground passage was a path shared by cyclists and pedestrians (for an illustration, see Figure 1).

Figure 1. Illustration of the intersection from a top-down perspective. The red rectangle indicates the participant’s position; the white line the current travelling direction; the tip of the green semicircle the current head orientation. Purple lines indicate the two intersection branches (highlighted by different background colours) visible from the
participant’s current position (i.e. whether the hitboxes indicated by a greyish background are in direct line of sight).

The virtual environment featured simulated pedestrians, cars, and motorcycles. Twenty pedestrians walked on fixed trajectories on the shared path and the sidewalks, but did not cross streets. The game engine spawned five vehicles, which appeared randomly at the beginning of one of the three street branches, and were randomly set to drive into one of the two other street branches (where they disappeared again). Up to two of the vehicles could be motorcycles, with the rest being cars. Cars were set to travel with a velocity of 30km/h (the speed limit of the respective real world roads). Motorcycles were set to travel with a velocity of 40km/h, with the idea that they catch up to the car in the front, and were then less visible and potentially more surprising for the participants. Both cars and motorcycles indicated turns with blinking lights on the right or left and respected the right of way. A honking sound sounded when a participant was within a 10 m distance in front of the vehicle.

The VR environment was shown from a first-person perspective of a cyclist sitting on a bike, with a height of about 1.6m. A virtual bike model (but no avatar) was included in the VR environment. The handle bar and the front wheel moved according to the participant’s input (see next section). A semi-transparent white arrow with length and orientation reflecting the participant’s speed and traveling direction was included to provide participants with a better sense of speed and spatial orientation in the VR environment (for an illustration, see Figure 2).
Figure 2. Illustration of the virtual environment as seen by the participants. The white arrow provided visual feedback about the current direction and speed of travel. The red line indicates the route participants were supposed to use in the current trial.

2.2.2 Technical apparatus

Participants sat on a swiveling chair and wore an Oculus Rift (consumer version 1) HMD with a resolution of 2160×1200 pixels and a horizontal field of view of about 90°. The virtual bike was controlled with the Oculus touch controllers. The main trigger button of the left hand controller was used to accelerate; the main trigger of the right hand controller was used to brake. Steering was achieved by rotating both touch controllers around a virtual fix point, thus approximating the control of a real-world bike handlebar.

2.2.3 Questionnaires

One questionnaire was presented within the VR environment immediately after arriving at the destination of each trial (see Section 2.3). Participants were positioned at a viewpoint high above the (virtual) ground of the intersection, so that all intersection branches were clearly visible with minimal head movements (see Figure 3). There were neither vehicles nor pedestrians. A colored
line indicated the path travelled in the respective trial. For each intersection branch (with the exception of the one the trial had started at), a vertical ruler with a scale from 1 = ‘not dangerous at all’ to 7 = very dangerous’ was presented simultaneously. The default rating for each ruler was set to the maximum value to avoid floor effects. A written statement presented in a white box asked the participants to indicate “How dangerous do you consider the intersection branches, respectively?” Participants used the analogue stick of one of their motion controllers with their thumb to switch between the three rulers by pressing left or right, and to rate the hazard level on each ruler by pressing upwards or downwards. Participants had to adjust the rulers of all three intersection branches before they could proceed.

After finishing the main study in the VR environment, participants received a pen- and paper-questionnaire. The questionnaire included demographic items assessing the participants’ age,
gender, and native language (see Section 2.1). Several items assessed the participants’ cycling experience and their experience of the virtual environment. As can be derived from Table 1, most participants reported to be frequent cyclists. The VR environment and the cycling simulation created a medium level of immersion. Some of the participants who completed the study experienced symptoms of cyber sickness, but reported only minor impairments concerning their ability to complete the required tasks.

Table 1. Items assessing cycling experience, immersion, and cyber sickness, as well as their mean descriptive values.

<table>
<thead>
<tr>
<th>Item</th>
<th>M (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cycling experience</strong></td>
<td></td>
</tr>
<tr>
<td><em>How often are you cycling in the city?</em> (1=’never’ to 7=’very often’)</td>
<td>5.00 (2.03)</td>
</tr>
<tr>
<td><em>How do you judge your cycling skills?</em> (1=’very poor’ to 7=’very good’)</td>
<td>5.42 (1.35)</td>
</tr>
<tr>
<td><strong>Immersion</strong></td>
<td></td>
</tr>
<tr>
<td><em>How natural felt looking around in the environment?</em> (1=’very artificial’ to 8=’completely natural’)</td>
<td>4.70 (1.46)</td>
</tr>
<tr>
<td><em>Did the VR experience match your real world experiences?</em> (1=’not matching’ to 8=’completely matching’)</td>
<td>4.15 (1.35)</td>
</tr>
<tr>
<td><strong>Cyber sickness</strong></td>
<td></td>
</tr>
<tr>
<td><em>How strong were symptoms of cyber sickness you noticed?</em> (1=’not at all’ to 8=’very strong’)</td>
<td>3.40 (2.06)</td>
</tr>
<tr>
<td><em>How much did cyber sickness distract you from completing your task?</em> (1=’not at all’ to 8=’very much’)</td>
<td>2.65 (2.25)</td>
</tr>
</tbody>
</table>

2.3 Procedure

Participants were tested alone or in pairs, but performed the study individually on identical technical apparatus. Their informed consent was obtained in written form before they could continue with the study. They took place on the swivel chair and the experimenter helped them to put on the HMD. Their seating position was aligned with the virtual bike. They were instructed to imagine cycling at the presented locations.

In an initial practice phase consisting of a figure-of-eight street featuring two cars, participants familiarized themselves with the controls and manoeuvring the virtual bike.
The main part of the experiment consisted of twelve trials. In each trial, participants started at one of the four different intersection branches (see Figure 1). A red line on the ground showed the route they were supposed to travel, which ended in one of the other three intersection branches and was indicated by a stop sign. Each participant travelled from all four starting points into all three intersection branches, presented in random order. After completing a trial, participants worked on the questionnaire concerning the hazardousness of each intersection branch (see Section 2.2.3). After completing all twelve trials, participants worked on the pen-and-paper questionnaire before they were thanked and debriefed. The whole study lasted about 30-45 minutes.

2.4 Categorization of intersection branch attributes

We defined three categorical indicators describing the four intersection branches and their relation to the traveling direction in each trial. First, we assumed that differences between the specific intersection branches could lead to general differences in the associated hazard level (Intersection branch). Second, we defined the position of each intersection branch relative to the general travelling direction of the participant when closing in on the intersection’s center, separately for each of the twelve trials (Position of intersection branch). These categories were ‘Front’, ‘Left front’, ‘Right front’, ‘Left back’, ‘Right back’. We assumed that the visual accessibility of intersection branches located ‘left front’ and ‘right front’ should be lower than those of intersection branches located in the ‘front’ direction. The visual accessibility of intersection branches located ‘left back’ and ‘right back’ should be even less. Third, we categorized the general type of turning a participant had to perform in a given trial (Turning type) into ‘Straight’, ‘Normal turn’, ‘Sharp turn’, ‘Offset’. For an illustration, see Figure 4.
Figure 4. Illustration of the turning types and the positions of the intersection branches relative to the traveling direction in four of the twelve trials. The black lines indicate the schematics of the intersection; the letters in circles reference the four intersection branches. The blue dotted line indicates the path travelled in the respective trial. The categorical position of each intersection branch relative to this travelled path is presented in italics.

3 RESULTS

The results section is divided into two parts. First, we investigate which factors affect the risk attribution to the different intersection branches. Second, we turn to the possibility of using an HMD to gather insights into participants’ gaze behavior.

3.1 Risk attribution to different intersection branches

We constructed a linear mixed models with the hazard level estimate as the dependent variable. Intersection branch, Position of intersection branch, and Turning type were included as independent variables. The participant's IDs and the path ID were added as random effects, resulting in the following model (see Table 2 for details):
Hazard level estimate ~ intersection branch + relative position of intersection branch + turning type + (1|participant.ID) + (1|path.ID).

Table 2. Parameter estimates of the linear mixed models. AIC = 2,844.77. * = p < .05, ** = p < .01, *** = p < .001.

<table>
<thead>
<tr>
<th>Factor</th>
<th>B (SE)</th>
<th>df</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>3.52 (31)</td>
<td>709</td>
<td>11.52***</td>
</tr>
<tr>
<td>Intersection branch</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(A)</td>
<td>-1.32 (.25)</td>
<td>709</td>
<td>-5.24***</td>
</tr>
<tr>
<td>(B)</td>
<td>.00 (.22)</td>
<td>709</td>
<td>.00</td>
</tr>
<tr>
<td>(C)</td>
<td>-1.10 (.20)</td>
<td>709</td>
<td>-5.42***</td>
</tr>
<tr>
<td>(D)</td>
<td>.00 (.00)</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>Position of intersection branch</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left back</td>
<td>-.15 (.32)</td>
<td>709</td>
<td>-.46</td>
</tr>
<tr>
<td>Right back</td>
<td>.30 (.33)</td>
<td>709</td>
<td>.91</td>
</tr>
<tr>
<td>Left front</td>
<td>-.01 (.29)</td>
<td>709</td>
<td>-.04</td>
</tr>
<tr>
<td>Right front</td>
<td>.04 (.29)</td>
<td>709</td>
<td>.81</td>
</tr>
<tr>
<td>Front</td>
<td>.00 (.00)</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>Turning type</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal turn</td>
<td>.52 (.22)</td>
<td>709</td>
<td>2.42*</td>
</tr>
<tr>
<td>Sharp turn</td>
<td>1.03 (.25)</td>
<td>709</td>
<td>4.20***</td>
</tr>
<tr>
<td>Offset</td>
<td>1.25 (.24)</td>
<td>709</td>
<td>5.27***</td>
</tr>
<tr>
<td>Straight</td>
<td>.00 (.00)</td>
<td>.</td>
<td>.</td>
</tr>
</tbody>
</table>

As can be derived from Table 2, the intersection branches A and C were perceived as significantly less dangerous than the other two branches. Contrasting our expectations, there was no indication that intersection branches positioned further off the participant’s main travelling direction were rated as more dangerous. However, hazard estimates were generally higher when the respective trial’s traveling path included a sharp turn or entering an offset street.

3.2 Using a HMD to gather insights into participants’ gaze behavior

We speculated that the orientation of the HMD could provide insights into the participants’ gaze focus: The limited horizontal FoV (about 90° for the Oculus Rift as compared to about 220° for normal human vision) in combination with the virtual reality could require the HMD’s wearer to
orient the head more towards the area of interest. To investigate this possibility, we visualized a ray emanating from the central point of the HMD’s FoV. In a qualitative pre-test of three persons, we found that the location where this ray hit a spot in the VR did not align well with the area the HMD wearer reported to look at. This was particularly relevant when closing in on the intersection: Despite the limited horizontal FoV, the self-reported gaze focus was close to the FoV’s limit (due to lateral eye movements). The central ray would thus point towards a focus on one intersection branch, whereas the person reported to gaze at an adjacent intersection branch located about 45° to the left or right. We therefore conclude that the HMD’s orientation is a poor indicator of its wearer’s gaze focus.

4 DISCUSSION

The present research was designed to investigate the impact of the visual accessibility and the relative spatial position of street branches on cyclists’ risk attribution when crossing an intersection. For this purpose, we created a virtual environment featuring an intersection participants experienced through a HMD. Participants were asked to provide an explicit hazard estimate for each street branch of the passed intersection. This hazard estimate differed significantly between the street branches. Contrasting our expectations, we found no evidence that the spatial position of an intersection branch in relation to the traveling direction affected the participant’s hazard estimate. In other words, according to our results, intersection branches located more to the right or left are not perceived as subjectively more dangerous, although it should be more difficult to spot cars approaching from these directions. However, the hazard level did differ depending on the way the intersection had to be crossed (e.g. a sharp turn and an offset of the opposite intersection branch increased the hazard estimate). Thus, it could be argued that the complexity of the required turning manoeuvre in combination with the visual accessibility may affect the hazard perception of the entire intersection more than that of
specific intersection branches. Obviously, it is possible that an intersection branch’s direction truly has no effect on the risk attributed to this intersection. However, several aspects of our specific implementation may have supported this null-effect.

4.1 Lessons learned, and design of a follow-up study

This study represents our first approach to study cycling safety in a VR setup featuring a HMD. Despite the generally promising impressions, we draw several conclusions that might be relevant for future research approaches in this direction.

First, there are two issues related to the technical setup of our study. Our simulation of riding a bike was mostly limited to the VR presentation itself. In contrast to other studies (e.g. Nazemi et al., 2018; van Paridon et al., 2021), we did, for example, not seat participants on an exercise bike requiring them to pedal for virtual movement. Although this undoubtedly increases the participant’s level of immersion, we believe that it is not necessary to strive for realism in cycling simulators in order to gain valid insights into cycling safety. Every feature included to enhance the realism of the bike simulator is prone to highlight the absence of another feature. For example, enabling ‘natural’ pedalling and steering on an exercise bike may feel off to participants, as they cannot lean into the turning direction, as they would on a real bike. Including additional features in a bike simulator may thus greatly increase the technical complexity, only to create an experience similar to the ‘uncanny valley’ proposed for interaction with robots and avatars (Mori et al., 2012). However, from our own testing of the VR environment, we felt that the closer the seating position and the handling of the motion controllers resembled to that of riding a bike, the more intuitive, comfortable, and natural felt riding the virtual bike. It thus appears important to use simple cues associated with biking to support the participants’ ability to immerse themselves in the VR.
Furthermore, HMDs allow a very natural viewing behaviour and support the participants’ immersion. However, it was our impression that due to the limited horizontal FoV, it is much harder to perform a quick shoulder glance to check for cars approaching from the rear. Such quick head turns in the VR (which are an important part of real world cycling) are also one common source of cyber sickness, even with a reasonably low latency of the technical apparatus. There are recent HMD models featuring a much wider horizontal FoV, but this limitation may be hard to overcome for the near future, and should be kept in mind when drawing conclusions from VR based studies on real world cycling.

Second, we used a single intersection participants crossed multiple times. This intersection was designed to resemble a real-world intersection, with the aim to generate a natural impression. However, this also meant that participants were becoming increasingly familiar with the environment. Furthermore, this also resulted in several limitations linked to the distribution of specific turning types, or the position of the intersection branch used by cyclists and pedestrians only.

We are currently designing a follow-up study addressing these issues. We developed an algorithm generating a route based on different tiles (see Figure 5). Intersection tiles are designed with one entry direction and eight potential exit directions. The actual number and position of the exit directions is randomly generated and can be limited and adapted according to the research question. Houses, greens, or parking lots automatically cover the other (potential) exit directions. After each intersection tile, a connector tile generates a road link to the next intersection tile, without obvious disruption for the participant. This approach allows us to present a series of intersections with standardized features, which nevertheless are unique and novel for the participant.
Figure 5. Illustrations of the follow-up VR. The *middle panel* shows the automatically generated tile-based network of intersections. The route starts on the tile with the red outline and follows the blue dotted line to the tile with the green outline. Please note that only the intersection tiles are shown, and connector tiles are omitted for visual simplicity.

The *right panel* and the *left panel* show a bird’s view of two different intersections with the entry direction at the bottom and two open exit directions each. Roads, greens, or parking lots cover the other six potential exit directions. The bottom half of the left and the right panel show the egocentric perspective as seen by the participant.

The direction the participant is instructed to use is presented on a simulated navigation assistance within the VR, thus requiring a more active navigation by the participant. Corresponding to the study reported in this research, the hazard level of each intersection branch is assessed after successfully crossing the interaction. After a first pre-test, the updated approach appears to reduce the limitations and confounds of the current VR environment. We hope that this will allow us to gain a more solid insight into cyclists’ risk attribution of different intersection branches.
5 CONCLUSIONS

The present research used a simple VR setup featuring a HMD for natural gaze behaviour to investigate cyclists’ risk attribution of different branches when crossing an intersection. Contrary to our assumptions, we found no evidence that visually less accessible intersection branches (i.e. those located more to the right or left relative to the travelling direction) are generally estimated as more dangerous. However, sharp turns and an offset of the travel direction led to higher hazard ratings. We identified several shortcomings of our approach we hope to address in a follow-up study.

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