Effects of Visual Cues of Wind on Perception of Wind and Cycling Speed

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***Abstract*— Drawing from findings on visual dominance in the field of multimodal perception and the role of wind in everyday life, effects of visual cues of wind in multimodal scene perception and its reflection in behaviour are examined. This study evaluates perception of incongruent multimodal cues of wind and its reflection in cycling speed. In a within subject experiment, 33 subjects were exposed to two wind conditions during a one kilometer long cycling trip in a virtual environment. Wind was represented by visual and haptic cues, while the haptic stimulus was static. First, a weak environmental wind was visualized that halfway transformed into a strong wind condition (this order was counterbalanced). Wheel rotation duration over time, subjects' experience of the trip and immersive tendencies were measured. No effects of changing visual cues of wind on wheel rotation duration were found. Mean wheel rotation duration decreased between the first and second condition for almost all subjects: those starting in the weak wind as well those in the strong wind condition. The most important finding is that subjects were aware of the incongruency of haptic and visual cues but still felt affected by both. They self-reported they increased cycling speed because wind force increased, which suggests a relation exists between exposure to visual cues of wind, and cycling behaviour in such a way that people tend to increase their cycling effort when wind seems to become stronger. Further research is needed to determine whether this possible relation exists in behaviour, rather than in perception of behaviour. We review the methodology and propose possible adaptations of the research design for future studies.**

***Index Terms*— cycling, multimodal processing, wind, virtual environments, incongruent multimodal stimuli.**

1 Introduction

The environmental factor wind is present in everyday life. It affects our abilities to move and the energy we spend to behave in the outside world. In general, weather conditions are of great influence on our mood an individual physical state. First, because we speak about it so often, our attitude towards going outside changes day by day, based on whether the current weather state feels attractive to do so. The conditions we are exposed to, when travelling outside to our work by foot or bicycle or when we are just standing outside, also have some direct physical influence on our bodies. When it is raining, our skins and clothes obviously become wet. When there is a strong wind, hair may become tousled and while cycling, headwind makes it more exhausting to reach our destinations.

Also in less direct ways, wind is an influential source of information. While walking, cycling or just sitting in rest, we experience the feeling of air touching our faces and other body parts. Wind force- and wind direction perception, play an important role in perception and action. Perception of wind direction contributes to our spatial orientation [1] and affects our perception of speed [2]. For specific contexts in sports, wind plays an even more directly influential role. An outstanding example is sailing. For sailors, being able to estimate wind direction and force is important to define future tracks and trim the sails. Cutaneous sensation from wind, without the presence of any real motion, can induce self-motion perception [2]. These phenomena stress the importance of information gathered from the haptic system in general and more specifically, of the role of cutaneous wind sensation in overall perception.

However, wind conditions are not solely perceived via the haptic perceptual system. Phenomena such as flowing water, waving flags and trees and moving ice, suggest a presence of wind that has a certain direction and force. We use these visual stimuli to estimate some weather conditions and the effect they will have on our physical state, when we go outside. When we look out the window on a bright winter day, the environment looks calm and the sun may shine. But this does not mean it is warm outside yet. Just as when we see trees bending because of the wind, this does not mean the wind will also affect our cycling performance. The winds may be stronger at the specific location of the trees, or we only saw the results of an incidental wind gust when one of those trees bended so heavily. In this research, we address the influence of these visual cues of the presence of wind, on the haptic perception of wind, and see how this is reflected in human behaviour.

The environment around us presents all kinds of phenomena influencing our perception. These stimuli differ in their nature (physical material, medium) and in the way humans can process them: the different sensory receptors of our perceptual systems and different brain areas process different qualities of incoming information. Information received by these different sensory modalities, is combined into one coherent perceptual experience. When perception is built up of information spread across different sensory modalities, the process in where a coherent representation of information is generated, is called multisensory integration or cross modal perception [3][4]. In the creation of this coherent logical experience, some sensory channels are more likely to affect our overall perception than others, meaning that some sensory systems dominate over others [5]. Within this idea, it is known that in general the visual system is dominant over the haptic system [6][7][24].

When we experience a certain wind condition, we got this perceptual experience not only via cutaneous sensation as well as via our visual system. This leads to the question what happens when visual and haptic cues, contradict: where do we base information on? Does our visual system interact with actual haptic wind perception? Drawing from findings on cross modal perception, the notion of visual dominance and the role of wind sensation in human perception, we investigate the interaction between the visual and the haptic perceptual system in the perception of wind and thereby focus on the reflection of this interaction in cycling behaviour. A novel method has been designed to study cycling behaviour in different wind conditions. We ask people to perform a cycling trip in a virtual environment while they are exposed to certain wind conditions presented through both visual as well as haptic cues and see what the effects of incongruent multimodal cues, on cycling speed are. We focus on two questions in the design of the experiment and the discussion of the results:

1. *How do incongruent haptic and visual cues of different wind forces influence cycling speed?*
2. *How do people experience incongruent haptic and visual cues of wind?*

Since wind is something we experience so often, whether it is conscious or unconscious, we have learned how our body movements are affected by wind and are able to behave according to that. If we perceive cues that usually are accompanied or followed by certain events that desire a change in the effort we perform, preparation processes of the body are induced [8]. This leads to the idea that also visual cues of wind, that are normally accompanied by corresponding actual wind conditions, are considered when adapting behaviour to changing environmental wind conditions.

In our situation, people see the wind is becoming stronger, which suggests it becomes harder to cycle in the environment and therefore a higher force should be used to maintain cycling speed. While these visual cues do not physically affect their cycling abilities, we expect people unconsciously start to put more effort into their cycling behaviour, because they feel affected by actual wind or expect to become affected by actual wind. They decrease output power, when wind is becoming softer. Cycling speed is equivalent to output power, when all other variables, such as resistance are kept the same. So, this increase of effort, results in a higher cycling pace in the end.

In conclusion, we define the following hypothesis: people increase their cycling speed, when the presence of actual wind is exaggerated through visual cues (it is storming) compared to a weak wind condition in where the amount of wind presented by visual cues is weak (a soft breeze).

1.1 Studying multimodal scene processing and behaviour in context

Multiple motivations lead to the choice of studying the context of cycling in a windy area in a virtual environment and focusing on behaviour, besides having people to mentally reflect on their experience. They both relate to the degree to which we can relate results from studies on multimodal processing to human behaviour in the real world.

First, studying interactions between sensory systems is often done by examining people's perception of multimodal stimuli. Instead of directly investigating the perception of wind force, we came up with a method to evaluate behaviour in situations where conflicting information appears. We avoid focusing on perception of incongruent stimuli in the first place so that people react to stimuli as they would naturally do. Hereby we may uncover direct effects of incongruent stimuli on unbiased human behavior. It already has been confirmed that cross modal sensory input not only influences perception, but is also directly represented in our behaviour (e.g. [27]).

Secondly, studies on interaction effects in multimodal processing, often evaluate the perception of single and clear objects, rather than scenes (e.g. [6][27]). The way objects are displayed is specific to a laboratory setting, and does not represent the way they are occurring in real-life. It is efficient and safe to study objects and simple situations in an isolated way to be able to conclude on effects of specific stimuli. But in real-life, we never react to single objects or phenomena while ignoring the context they appear in. “Our visual world is a stimulating scenery mess”, as Moshe Bar writes in his Book Scene Vision (p.7) [9]. To study the effects of visual cues of the presence of wind on human behaviour, we believe it is important to acknowledge this for not only the visual system, but for the whole perceptual system functioning in the real world, with all its stimuli affecting our different sensory systems. This direction of thought is supported by a call for papers that appeared on the website *Frontiers* in 2015, challenging researchers to study multimodal interaction in the real world, instead of focusing on experimental control [10].

We aim to study human behaviour in a context that relates to the natural world. The choice for the context of the activity of cycling in a windy environment has been made because it is a situation that can be related to our real-world experiences. Wind is meaningful to real world cycling because required output power during cycling to maintain a certain speed, is affected by wind conditions. The presence of wind, negatively affects cycling performance [11]. People who regularly cycle, already have noticed this in real-life, so we can use their knowledge to see what happens when we transform visual cues of wind to cues that do not correspond to the actual wind condition, which does not happen in real-life.

As a final motivation, we chose to use a virtual environment to resemble a scene because of possible interesting ways to present incongruent stimuli. Since wind itself is not visible, a scene needs to be present that can be affected by this wind when one wants to present visual stimuli of wind. This makes it a suitable example of a context that should be studied in a real world like scene: a scene where objects are affected by wind. Because we regulate wind conditions to see how people react on changing visual stimuli of wind, we should keep looking for the right balance between reality and control all the time. Making use of a virtual scene, offers this possibility.

By studying multimodal processing through evaluating behaviour in virtual environments, we aim to explore methods that enable researchers to generalize results in the realm of realistic, whole scenes. Hereby we try to challenge the current experimental paradigms in multisensory processing. Besides the interaction between perception of visual and haptic cues of wind itself and its reflection in behaviour, we will therefore evaluate the used methodology to provide ideas and improvements for future research in multimodal processing.

1.2 Implications

Visual cues of wind presented in a virtual environment influencing action or perceived physical state after executing a certain action, could indicate that also visual cues on wind are taken into account when perceiving wind and acting according to gathered information. This would support the more general statement that our perceptual systems show interaction effects and thereby our general perception is made up of information perceived through different channels, whether or not certain channels offer meaningful information. This provides valuable information on how coherent experiences are constructed and what the role of visuals cues in this process is. More applied, this can be valuable information for training of experts for whom handling different wind conditions is important, such as sailors and pilots.

In addition, answers on these questions contribute to research and applications that intend to increase immersion of people in a virtual environment. Wind has been studied as a potential factor to increase realism through the haptic modality as either a force feedback medium to provide sensation of touch (e.g. [13]), or when wind is presented as an environmental factor in a virtual environment [14][15][16]. This has shown to increase a feeling of presence [17][18], enhance situational awareness and even improves user performance on navigational tasks [14].

Other studies focus on the actual design requirements of wind displays as part of a virtual environment and examine the discrimination performance people show while indicating wind directions [16][19][20][21]. Knowledge about the value of visual and haptic cues in wind perception and the way it affects human action, may offer ways to improve the implementation of wind displays in virtual environments. For example, if it is known that visual cues of wind deviating from the actual wind enlarge range of perceived wind forces, it can be decided to enlarge the range of presented wind force in an application through graphics on the software side, rather than through expanding on the hardware side of the physical wind device.

In this paper, we first discuss related work on the main themes cross modal perception and wind (Section 2. Related Work). After, a method is proposed to study interaction effects between visual and haptic cues of wind. We investigate cycling speed of participants in a virtual environment, where haptic and visual cues of wind are present and evaluate participant's experience of the cycling task (Section 3. Method). In section 4, the results will be presented. In section 5, a general discussion is provided and we will evaluate the use of the proposed method to study multimodal processing and behaviour in real world like context.

2 Related Work

In this section, we discuss results from important studies done in the field of cross modal perception. Thereafter, we shift to studies that focus on the importance of the visual system in sensory interactions. Next, we review how behaviour is dependent on sensory interactions. Finally, we look at wind perception and existing studies that use wind or cycling elements in their setups.

2.1 Cross modal perception

The issue on how streams of information are integrated in such a way that they make up a coherent logical experience, is often referred to as 'the binding problem' by scientists as well as philosophers [22]. This problem could be viewed from the perspective of one sensory domain, for example when different attributes of an object are all sensed by the visual system, such as the shape, color, form and motion of one object. But when we perceive our environment, we are exposed to more kinds of stimuli, each speaking to one of our sensory systems. We use our visual as well as our haptic modality to perceive the current state of the environment. Multimodal perception refers to perception of information perceived through different sensory modalities simultaneously. To study interaction patterns between these sensory modalities, multiple studies are investigating the perceptual experience of people when they are exposed to conflicting stimuli each speaking to a different part of the perceptual system.

The McGurk effect is a famous example observed through one of these experiments. In this study, McGurk and MacDonald investigated the influence of visual information on speech perception. They showed that perceived lip movements strongly influence the perception of speech. Videos were constructed in where lip movements did or did not correspond to the actual spoken sounds. Participants were asked to repeat what a videotaped model was saying in two conditions: they faced the screen and viewed a model pronouncing a sound or turned away from the screens so that they only could hear the sounds. It turned out people were more accurate in the auditory only than in the auditory-visual condition [23]. This shows that visual and auditory cues interact when perceiving them simultaneously.

Rock and Victor [24] focused on the issue of the perception of contradictory information presented about the property of a physical object to the haptic and the visual perceptual system. They examined the perception of such an object and tested whether people were aware of the conflict. In three different experiments, participants were invited to manipulate an object with their hands, while they could not see it. A distorted visual representation of the object was presented. In this way, people perceived the object via both their visual as well as their haptic perceptual system, while these two systems provided incongruent information. People had to determine the shape of an object by matching other objects (either visually in the first and haptic in the second experiment) or redrawing the object in the third experiment. These matching and drawing tasks revealed that participants' impression of the shape of the object was in favour of their visual experience and only about 20% of 32 subjects were aware of the conflict [24]. This supports the finding of McGurk and MacDonald [23] that multimodal cues interact and in addition, that visual perception is strongly dominant over touch.

In the study of Rock and Victor, most subjects were not aware of the conflict [24], while still information from both modalities affected the overall perception. This indicates that people unconsciously use incoming information, and do not ask themselves if presented information is relevant or not.

2.2 Visual dominance and awareness

McGurk and MacDonald as well as Rock and Victor, focused on the powers of the visual sense as a distorting or altering source affecting other modalities: the haptic and auditory sense. Intersensory bias has been the focus of research of cross modal interactions for a long time. This bias refers to the degree to which perception of a stimulus presented to a certain modality (e.g. vision) is influenced by another modality (e.g. auditory), compared to when the first stimulus is presented as is. In general, visual stimuli have a strong bias on auditory and haptic perception [25][5][23][24][26].

Gibson was one of the earlier researchers that demonstrated the phenomenon of visual dominance. He asked people to wear prisms that made straight vertical lines look curved. When people had to describe the shape of the object while they watched their own hands touching the object, they reported that the objects also felt curved and did not experience a conflict [25].

Colavita [5] tested the attention people draw towards multisensory stimuli and their abilities to respond on them. People were instructed to press a key (R1) when a light (S1) appeared and another key (R2) when they heard a tone (S2). In almost all the conflict trials, were the light and the tone appeared at the same time (S1+S2), people only responded to the light (R1) and they were not aware of the presence of the auditory stimulus. In another condition where they were told both stimuli could appear simultaneously, performance increased, but still people responded more often to the light. This shows that participants respond more often to the visual component (light flash) of an audiovisual stimulus (a tone), when presented with bimodal stimuli.

As mentioned by Rock and Victor [24], the issue of awareness is relevant in studies on cross modal perception. They mainly pose this in terms of subjects' awareness of the conflict. Subjects were not told the two cues (visual and haptic) were incongruent and most of them did not find this out.

When comparing different studies discussed, it seems that a phenomenon underlying this, is interesting as well. This is the degree of awareness of the presence of multiple cues and the ability to disconnect them again, that is highlighted in an earlier study [5] where in one of the conditions, subjects were told two multimodal stimuli could occur. Still their decisions were affected by the irrelevant stimulus.

In contradiction. in the study of McGurk and Macdonald, one could argue subjects were not even aware of the multimodality, since participants who faced the screen when repeating the sounds were initially not aware of the video as a visual and an auditory source of information, but just of the video as a whole.

A more recent study [26] showed that even when people are asked to only take attention to- and base decisions on one out of two presented multimodal cues, meaning subjects have knowledge of the multimodality and possibly also the incongruency, still interaction effects occur, in favour of the visual stimulus. Lukas and Koch [26] studied the influence of this selective attention on the visual-dominance effect using a task switching paradigm. They present a visual stimulus by showing a shape on either the left or right side of the screen and an auditory stimulus (a tone played to the right or left ear) in each trial. Participants were asked to direct their attention to a specific modality and decide on which side the relevant stimulus appeared. This reveals more about the actual strength of the interaction between sensory systems. Even when people are explicitly asked to pay attention to one modality and ignore the other, interaction effects occur. More general, this also suggests that known irrelevant information presented, still affects the perception of an object or phenomenon that is relevant for the observer.

The methods used in the previous study, could form a point of discussion in the case when one wants to study natural multimodal processing. When people are consciously aware of irrelevant stimuli, these stimuli may alter people's usual decision making methods and their perception and behaviour may not correspond with original situations, even if they are not consciously aware of the conflict.

2.3 Multimodal perception and action

Studies mentioned above, specifically examine people's perception. To see what the actual role of cross modal integration is in general behaviour, it can be interesting to study people's actions rather than have them to reflect on an experience. We will not focus on solely on the perception of people of certain wind conditions based on multimodal input, but try to reflect on how people adapt their behaviour according to the situation when irrelevant or relevant stimuli change.

It has been confirmed that cross modal sensory input not only influences perception, but is also reflected in our behaviour [27]. Ban and Yuki used the idea of visual dominance in cross modal perception, with augmented reality techniques, to change the visual appearance of a dumbbell. They hypothesized that people would perceive brighter colored objects as lighter and darker colored objects as heavier. They examined fatigue after weight lifting with bright and dark colored dumbbells and found higher fatigue in people who had to lift the darker colored dumbbell [27].

Expected weight in combination with the presentation of modified visual stimuli has been studied before extensively. The size weight illusion, is an interesting example that refers to the fact that people tend to underestimate the weight of larger objects when comparing it to another smaller object with the same mass [28].

Expected weight in combination with visual stimuli, also has been studied when visual stimuli are presented independently and external from the object that should be judged. Hershberger and Misceo [8] focused on the influence of the presentation of one (irrelevant) stimulus on the action preparation process for- and perception of another stimulus. They asked 20 females to judge the weight of an object that was dropped repeatedly in their hand. Before (group 1) or at the same time of the drop (group 2), another stimulus was presented: an indicator lamp was activated. In the beginning of the experiment, subjects got the chance to evaluate the weight of two objects at the same time and were told they differed in weight (while they actually had the same weight). During the experiment, one object was dropped 180 times, but subjects did not know it was the same object every time. They were instructed to determine for every trial if the lighter or the heavier object was dropped. They perceived the object as the lighter one when the activation of the lamp preceded the drop of the object than when there was no lamp activation. This did not happen when the light was presented simultaneously with the drop of the object. This shows that people learn to exert effort if they perceive cues that are followed by certain events that they think need a certain effort.

Ban's findings on perceived exertion after a physical activity [27] show that even a dynamic activity as weight lifting can be affected by cross modal sensory input. In this example however, it is still one clear physical object providing the stimuli (a dumbbell) related to a local task (weightlifting) rather than multimodal stimuli arising from different positions in a wider scene.

The study of Hershberger [8] shows that even external visual stimuli can affect action, and more importantly, clearly show that not so much actual perception of haptic cues affect effort we give, but the expected haptic effort needed does. Based on this, we pose that since wind is something we experience so often, whether it is conscious or unconscious, we have learned how our body movements are affected by wind and can behave according to that. If we see cues that indicate a certain quality of wind, we start to put effort into our cycling behaviour, according to our expectations of actual wind conditions.

We will resemble a real and more complex scene that includes multimodal conflicting stimuli (haptic and visual). In this way, we hope to be able to support these findings, that multimodal perception is reflected in behvaiour, even in a dynamic situation as cycling in a virtual windy environment.

2.4 *Effects of wind in everyday life*

While probably all people can imagine themselves being affected by strong winds when performing activities outside, we feel it is relevant to show that multiple researchers have put effort into evaluating the effects of wind on people. This mainly happened in the context of building design (e.g. [29][30][31][32][33]). Researchers have defined wind discomfort criteria to adapt building designs to meet people's needs in the realm of experiencing winds around buildings.

To give an example, we will describe one of the early experiments that illustrate well how research on the effect of wind on people has been done. Hunt's experiment [31], participants were invited to execute a few simple everyday activities, while standing in a wind tunnel in wind speeds of 5 and 8.5 meters per second. Measurements were made on the steadiness and direction of walking of the volunteers when they entered the tunnel. Besides, subjective verbal reflections were given on multiple wind conditions between 4 and 12.5 meter per second. Each participant performed 9 activities: putting on a raincoat, putting on a scarf, finding a word on a page of the newspaper, filling a glass with water, crossing out selected words on a list and people had to assess the strength of the wind and the influence on their performance by putting a mark on a scale ranging from 'tidy' to 'blown about' on a piece of paper. Performance (measured time to complete each task) decreased when wind speeds, the amount of wind gusts and/or the amount of turbulence increased from a negligible level to that of the amount of a gusty wind in the city. Increased wind speed had a higher effect than turbulence [31]. This research on comfort criteria for wind conditions is based on the experience of pedestrians walking close to buildings in cities, so we will use this knowledge not so much as strict guidelines for our experimental setup but more as an inspiration and starting point.

Studies on wind comfort criteria, only look at the physical effect of wind and not so much at how different sensory modalities play a role in this, besides differentiating between mechanical effects and thermal effects, which are both experienced through the haptic modality. Since we are interested in multimodal scene perception and believe also visual information may play a role in this, we will discuss studies that focus on perception of wind through specific modalities.

2.5 *Wind perception*

Increasing user felt presence is one of the design goals for virtual environments [17][18]. It is often said that offering multimodal interaction, by providing information to users through different sensory modalities, increases and promotes this user felt presence. This motivates researchers to also include the haptic modality by evaluating the use of wind displays in virtual environments (e.g. [17][14][18][34][13]). These studies also provide interesting information on the general perception of wind and the value of wind perception in everyday life. Haptic feedback via wind can be used to draw the user's attention at a point of interest [34] and provide a sense of touch [13].

Travelling in virtual environments is different than in real environments because physical feedback apparent in real-life, such as feeling bumps in the road and feeling the wind blowing in your face are not present. Spatial awareness decreases which makes it harder to for example intuitively keep track of covered distance [7]. Deligiannidis, Leonidas and Jacob, defined travelling as one of the major problems in virtual environments and developed a device in the form of a scooter, including vibrotactile sensors and a wind display [14]. Users can feel the speed of travel via a fan providing an air stream and via vibration both depending on the speed of travel. Participants were invited to drive along a certain track in a virtual environment as fast as possible, while avoiding obstacles. When they bumped into an obstacle, a mistake was registered in the enhanced virtual environment, subjects performed better: the avoiding task was executed more accurate and people drove more carefully [14].

Furthermore, they found significant results showing an improvement in realism of the experience. These findings are supported by another study that presented a wind display by mounting a fan setup on a helmet to be used in a virtual piloting application [18]. This shows that haptic feedback in the form of wind and vibrations help users to achieve navigational tasks with more accuracy and inclines that also wind in real-life contributes to our sense of space and navigational performance.

In an actual cycling trial, perceived performance in different wind conditions in a wind tunnel was studied. Wind was proven to be actually beneficial for perceived performance [35].

The importance of wind experience for virtual sailing has been noted. Also in this study, it was found that wind enhances user felt presence and it was suggested that wind temperature also affects user experience [15]. This should be considered while developing the methodology.

In a different study the role of wind perception for blind people in relation to spatial orientation was examined. Researchers found that the presence of wind gives an orientation mark to people without vision during a sailing locomotion task [1].

Spatial orientation for Inuit is nearly solely based on wind. Inuit in Iglookik, an island that presents little topographic features that makes wayfinding a particular demanding task, use haptic as well as visual cues to determine their position in relation to the environment based on wind direction. Regarding the visual cues: patterns on the snow and moving ice are used, while for haptic cues known wind direction and force patterns related to specific areas and times periods are compared to current wind conditions and provide Inuit with an indication of their position [36]. Wind perception through purely visual information has been studied in the context of weather predictions. Because one cannot always rely solely on official forecasts in the US and Canada, people often evaluate the chance storms are arising by evaluating environmental cues by themselves. By this however, chance for tornadic storms is often underestimated, because visual features indicating a little tornadic situation, such as low darkness and high clarity, sometimes bias lay people to underestimate the tornadic features of clouds [37]. This shows that people's perception of wind is affected by visual features.

2.6 *Key Findings*

Key findings in the related work are summarized below. We base our hypothesis on these and that we will try to assess these with our mythology and in the discussion of the results.

- When perception is built up of information spread across different sensory modalities, the process in where a coherent representation of information is generated, is called multisensory integration or cross modal perception.
- Wind perception plays an important role in spatial orientation.
- Wind as an environmental factor in a virtual environment, increases user felt presence in virtual environments and improves performance in navigational tasks.
- Awareness of the incongruency of multimodal stimuli and the presence of multimodality itself is an interesting issue in studies on multimodal perception.
- If people are aware of incongruency of multimodal cues, their perception may still be affected by it and people cannot always disconnect cues.
- Visual stimuli have a strong bias on auditory and haptic perception.
- Cross modal sensory input not only influences perception, but is also reflected in our behaviour. It can influence physical activity and exertion.
- People can learn to exert effort if they perceive cues that are followed by certain events that they expect to need a certain effort. Preparation processes of the body are activated.

3 METHOD

3.1 *Goals and expectations*

We expect people to adapt their behaviour while cycling in changing wind conditions based on visual cues that indicate an environment to have certain qualities (a seemingly stronger or weaker wind force) and not solely on the actual haptic quality (the actual wind force), because of previous experience and expectations. This is in line with the general notion of visual dominance, the findings of how irrelevant visual cues affect behaviour [5][26][27] and the fact that preparation processes in our bodies are induced when we experience visual stimuli that we expect to be accompanied by certain consequences [8].

In our situation, subjects see the wind is becoming stronger. While this does not physically affect cycling abilities because actual wind is absent, we expect they unconsciously start to increase cycling effort (output power) because they expect to become affected by a strong wind. This results in a higher cycling speed. We define the following hypothesis: people increase their cycling speed, when the presence of actual wind is exaggerated through visual cues (it is storming) compared to a baseline condition in where the amount of wind presented to visual cues is weak (a soft breeze).

To test our hypothesis, a setup for a virtual cycling trip has been created, that simulates two different wind conditions. The conditions people are exposed to, are inspired by other studies done on cross modal perception, in where different sensory systems receive incongruent stimuli (e.g. [24]). Participants are invited to cycle on a stationary bicycle. We measure physical as well as psychophysical variables to be able to conclude on how behavior and psychophysical state depend on exposure to certain wind conditions with different degrees of visual cues supporting the presence of wind.

We make use of a virtual environment, because it is simply impossible to control outside wind conditions and secondly because it is unreliable to change real stimuli of actual wind conditions, into stimuli that contradict with the information they initially provide.

3.2 Stimuli

Figure 1 shows an overview of the different conditions people are exposed to in the virtual environment: a fixed actual wind is represented by a fan and two conditions represent an environment with understated (weak wind condition) and overstated visual cues (strong wind condition) suggesting the presence of wind. These conditions have been chosen so that comparisons of the results of the two conditions (the weak condition will be compared with the strong condition in the experiment) offer a way to see what the effects of visual cues of wind are.

Subjects cycle in front of a display that shows the virtual environment in where a certain presence of wind is suggested. A first-person view scenery was created using Unity 3D. Assets used were all available in the Unity Asset store. The environment consists of a field, a cycle path and a line of trees standing along this path. During the simulation, the point of view is moving along the cycle path, to provide participants with an illusion of movement in the actual scene.

This specific scenery has been chosen to emulate a typical Dutch situation of cycling on a cycle path on a dike in the countryside, where wind conditions are often easier to notice and affecting people's cycling abilities more than in cities. Thereby, through the absence of city like elements, we try to guide subjects to pay attention to the natural elements that indicate the presence of wind. In Fig. 2 and 3, a fragment of the scenery is shown from the weak wind condition (Fig. 2) and from the strong wind condition (Fig. 3). Three elements differ between the conditions: the magnitude of movement of tree branches, the amount and density of fog moving in the opposite direction of the viewer of the environment and the color and ambience of the sky. In the weak wind condition, branches of trees hardly move while in the strong wind condition they move severely as if it is storming. Wind direction is in the opposite direction, with the intention of subjects experiencing a headwinds situation. In the strong wind condition, also the sky moves in the opposite direction of the subject and the color of the sky is dark grey. In the weak wind condition, the sky does not move and the color is lighter. In the strong as well as in the weak wind condition, fog moves in the opposite direction of the subject, but in the strong wind condition, the density of the fog clouds and frequency of the appearance of the fog clouds is higher.

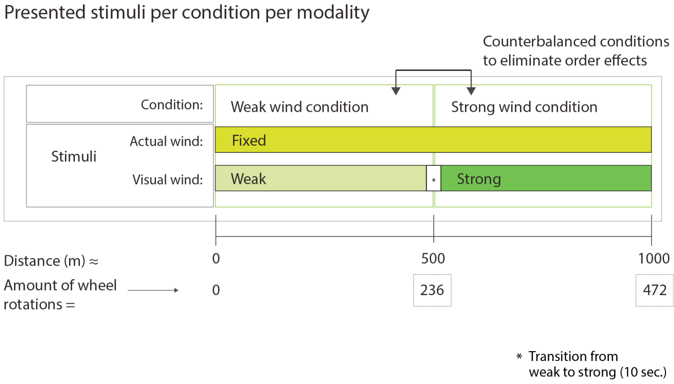

Fig. 1. Overview of the conditions presented to participants. The actual wind component is fixed and the visual wind component varies per condition. We define distances based on the amount of wheel rotations that have been made, but in reality participants will cycle approximately 500 meters in each condition (236 wheel rotations).

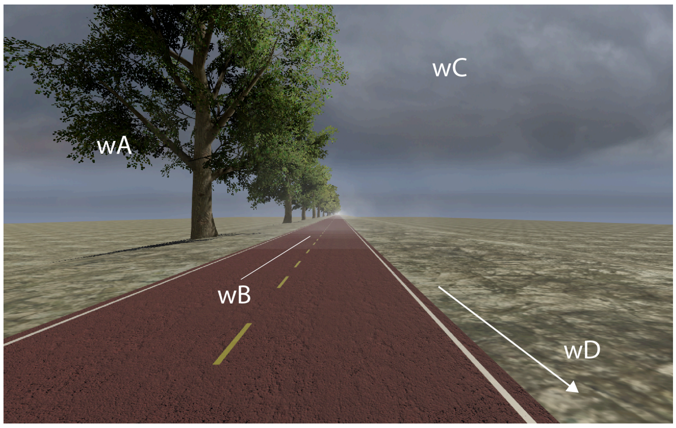

Fig. 2. Screenshot of the weak wind situation in the virtual scenery subjects are cycling in. Wind elements are wA: trees are not moving a lot, wB: little fog is shown, wC: the sky is light. wD: Movement direction of fog is towards the viewer.

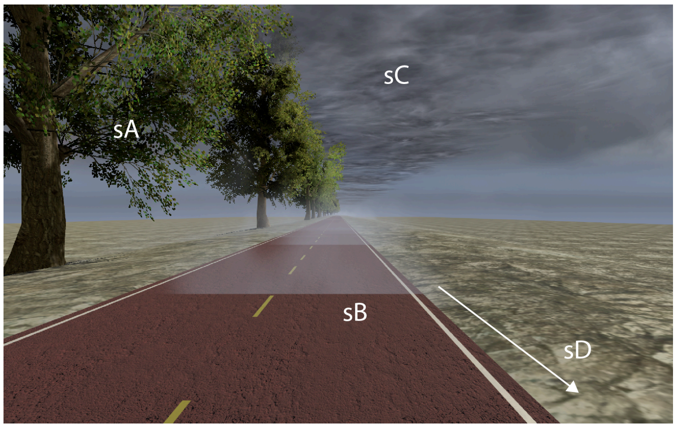

Fig. 3. Screenshot of the strong wind situation in the virtual scenery subjects are cycling in. Wind elements are sA: trees are moving severely, sB: fog is shown, sC: the sky is dark. sD: Movement direction of fog and dark clouds is towards the viewer.

The rise of the use of immersive virtual environments with head mounted displays (HMD's) together with virtual or augmented reality in psychological experiments (e.g. [27]) and the seemingly appropriateness of the medium to study scene perception could motivate us to use this medium as well. Nonetheless, a two-dimensional display is chosen to create the visual part of the environment for this experiment, because of multiple reasons. Since the head and especially the ears, are a very important part in perceiving wind force and direction [38], we do not want to cover those with a HMD to achieve haptic wind perception in the most natural possible way. Secondly, wearing such a device itself could distract users from the activity of cycling because of the novel character of HMD's in general, and the excitement this may evoke in participants. Finally, it could, in combination whit a physical activity such as cycling on a home trainer, lead to a feeling of disorientation in participants.

Because we only have access to basic machinery, we make use of an actual wind generated by a fan. By exposing people to this as a baseline actual wind and use two opposing sets of visual stimuli, we create two conditions that together with the constant fixed wind, resemble two situations in where incongruent stimuli are received by two different modalities.

Our experimental design is inspired by the research did by Ban and Yuki [27] who asked participants to weight-lift and examined endurance and perceived fatigue for different colored dumbbells. The main difference with that approach, is that we ask participants to execute one task, and provide both the two conditions (weak and strong visual cues indicating the presence of wind) within the duration of that task. The reason for this, is that we believe interaction effects of visual and haptic stimuli in multimodal scene perception are subtler, compared to those found in the clearer object perception tasks, investigated in studies mentioned before.

To be able to compare a participants' activities of the two situations, it is important he or she 'enters' the activity in the same physical and psychological state and does not become tired during the task. He or she should start cycling in the two conditions with the same feeling. We achieve this by presenting the activity as one whole. Subjects should not be motivated to find the difference between the first and the second test and their attention will not be directed at the changing visual stimuli provided in the two wind conditions. Subjects will experience the changing wind conditions in a natural way.

As was shown in an earlier study the application of wind during cycling trials, increases perceived performance. In the experiment, participants were asked to cycle as fast as possible for a certain amount of minutes [35]. Because we want people to attend to the environment and not to their own performance, we do not include a performance element and just invite subject to choose their own pace. Hereby, we do not expect such an increase in cycling speed because subjects do not have any incentives to cycle as fast as they can.

3.3 Measurements

To conclude on the interaction between the haptic and visual modality and its effects on human action, we will evaluate change in actual behaviour and inquire participants' experience of the task afterwards.

Wheel rotation duration: actual change in behaviour is measured by keeping track of the duration of complete wheel rotations made during the task (or: cycles). The variable we are changing (the visual cues indicating a certain wind condition) may affect cycling speed and thereby wheel rotation duration (WRD) over time.

Participants' experience of the virtual cycling task: to interpret the results from the cycling speed measurements, we evaluate participants' experience of the trip, after completion of the cycling task through questionnaires. The role of this questioning is two-fold: we want to assess participants feeling of presence and the perceived reality of the virtual environment to be able to asses to what level we can relate our results gathered in the experimental setup to multimodal perception and the coupling with action in the real world. Secondly, we evaluate participants' perception of specific elements in the virtual environment.

3.4 Experimental design

We make use of a within subject design. In this way, we eliminate potential group variability effects. If experienced cyclists are invited with roughly the same cycling level, a between group design could be considered. Yet, we believe that these people are focused on controlling their physical performance instead of taking attention to the environment and therefore their behaviour will not reflect the way they are affected by visual cues as in day-to-day activities. Thereby, potential found effects will be less remarkable for participants who are already naturally controlling their physical activity. For other people the cycling activity belongs to day-to-day activities. Furthermore, we counterbalance the condition with weak visual wind with the condition of strong visual wind, to avoid order-effects within the cycling task such as fatigue, which is a plausible effect due to the physical nature of the task.

Since we will make use of a within subject design, it is allowed that participants differ in age and physical abilities. As explained, we only exclude (semi) expert cyclists and professional athletes from the experiment.

3.5 Material and setup

The experimental setup consists of a speed bicycle (Columbus Squadra Course bicycle that was originally custom designed, but aimed at people with a body height of approximately 1.70 m). The bicycle was positioned into a stationary trainer, allowing one to cycle inside at a static position with resistance provided by a cylinder that rotates when the bicycle's rear wear does so. The bicycle is facing a screen (a Sharp LCD color TV, model 43CFE4142E) and a fan (Tristar Metal box fan, model VE-5935). We chose to use large 43-inch screen, to increase level of immersion (c.f. [39]).

A reed switch is attached to the rear wheel of the bike to register wheel rotations. The switch is attached to the left-button of a computer mouse so we can read incoming clicks via a USB-connection with a computer as wheel rotations. In Fig. 4, a schematic overview of the setting is shown. The computer (iMac, model: mid 2012) runs the application that provides visual cues for both conditions within a two-dimensional virtual environment, through the screen facing the participant. The blowing direction of the fan was chosen in the beginning of the experiment, during tests of the setup in such a way that it was directed at the face of the participants and was not adjusted for specific participants. The application (created using Unity 3D in C#) calculates time in milliseconds between to wheel rotations to define WRD (WRD) and processes this information to adapt the speed at which the virtual environment passes by, according to it. In this way, we create a situation that invites the participant to feel as if he or she is cycling in the environment that is shown (see Fig. 5). In both conditions, the fan used in the setup blew at its strongest speed, resulting in an airflow of approximately 2.0 m³ / second (taken from the fan's specifications).

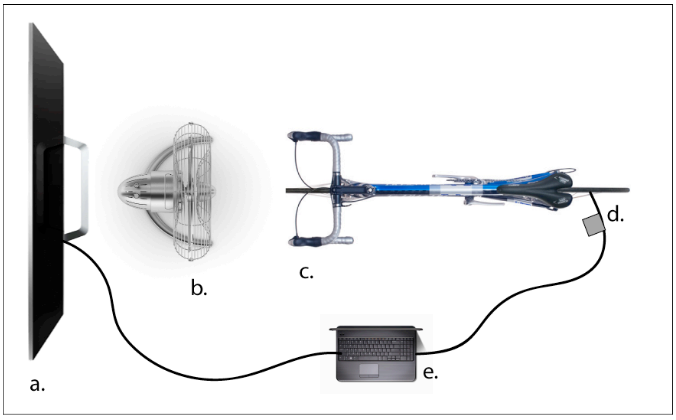

Fig. 4. Overview of the experimental setup. A two-dimensional screen shows the visual part of the virtual environment and provides the visual cues of wind (a). A fan is the source of haptic cues of wind (b) and a bicycle on a stationary trainer (c) faces the fan and the screen. Complete wheel rotations are tracked by a reed switch attached to a computer mouse (d) and processed by the application running on a computer (e). The wheel rotation duration is used in the Unity application as speed at which the environment passes by so that virtual speed on the screen (a) corresponds to the participant's cycling behaviour.

Fig. 5. The setup being used by one of the test participants. If he starts cycling, the environment passes by as if he is moving inside of it.

3.6 *Experimental procedure*

The 33 participants were recruited based on their willing to take part and their availability during the period of the experiment. Each participant was invited to a room in the building the Leiden Institute of Advanced Computer Science of Leiden University (The Netherlands). In total, the experiment took between 15 and 30 minutes to complete per participant. The duration depended on the subject's cycling speed, speed of reading and answering questions, and the time that was needed to find a comfortable position on the bicycle.

Subjects were first asked to read and sign an informed consent form and fill in a general information form (age, gender, cycling experience and habits and exercising habits). After this, the main experiment began with the cycling task, followed by a questionnaire on participant's experience of the task, a short semi-structured interview and ended with an immersive tendencies questionnaire. All procedures were executed in English, except for the semi-structured interview that was conducted in Dutch when the participant preferred this.

3.6.1 *Cycling task*

Participants were invited to take place on the bicycle, find a comfortable cycle position and adapt the saddle height if they preferred. We told participants we are studying different navigation methods in virtual environments and its effect on situational awareness. We requested participants not to use the breaks and gears and not try to steer the bicycle during the task. They were given instructions by reading the following text that also emotionally prepares them for the cycling task:

"Please have a look at the screen in front of you. You are going to cycle on the cycle path you see on the screen. You are now at the university and at the end of this road is your home, which is 1 kilometer from here. During the whole trip, it is important to try to imagine you are cycling on the cycle path as if you are really there, so please, take some time in the beginning to imagine you are cycling from the university to your home. Keep looking at the screen the whole time."

Participants were told the cycling trip is not a physical performance test and they could decide for themselves how fast they wanted to go, but that it is important to try not to cycle too fast, so that they would not get tired along the way. We thereby requested them to keep cycling during the whole activity.

"During the task, I will be sitting behind the wall, so you have space here to become immersed in the environment and so that you do not feel observed by me. In the beginning of the track, the fan will start blowing. At the end of the track, you will be informed you can stop cycling via the interface on the screen. During the experiment, we will not talk anymore unless you want to stop with the experiment, so if you have any

questions, you can ask them know. You now get some time to find a comfortable cycling position. When you have found a comfortable position and cycling speed let me know."

The participant started cycling now to find a comfortable position and natural cycling speed (we will refer to this phase as the *comforting process* in the rest of this paper). Cycle duration of every full wheel rotation is logged from the moment the participant started cycling. When the participant mentioned he or she found the right position and was comfortable, the experimenter left the setup area, activated the fan and logged current time by pressing a key on the keyboard. This allows to later excluding cycling data from the analysis that was gathered during the comforting process. The experimenter sat out of sight of the participant, but could hear if the participant was cycling and if everything was fine.

When the participant reached the end of the one-kilometer-long cycling track, the experimenter immediately deactivated the fan and entered the setup area again. For most participants, the cycling task took a few minutes (about 2-6) from the moment the comforting process ended.

3.6.2 Experience of the cycling task

To interpret the results from the cycling speed measurements, the subject is invited to fill in a questionnaire and we conduct a short semi-structured interview to collect observations we were not able to foresee beforehand. The questionnaire consists of two sets of questions: a *Feeling of Presence questionnaire* (FPQ) and a set of statements that requests subjects to evaluate their perception of specific elements they encountered during the cycling task (Perception of Specific Elements Questionnaire, PEQ). The participants were given a printed copy of the questionnaire.

3.6.2.1 Feeling of presence questionnaire

The feeling of presence questionnaire (FPQ) is included to assess participants' feeling of presence during the cycling trip and the perceived reality of the virtual environment to be able to evaluate to what level we can relate our results gathered in the experimental setup to multimodal perception and the coupling with action in the real world. Items included (8 in total) are taken from the validated presence questionnaire of Witmer and Singer [41] to validate level of presence in virtual environments. A few examples of items we included:

FPQ1: How involved were you in the virtual environment experience?

FPQ3: How compelling was your sense of moving around inside the virtual environment?

FPQ7: How much did your experiences in the virtual environment seem consistent with your real-world experiences?

These 8 likert items (FPQ1-FPQ8) require a response on a 7 step Likert scale ranging from 'not at all' to 'somewhat' to 'completely'.

3.6.2.2 Specific perceptual experience

Through a list of 14 custom designed statements, we assess participants' experience of specific elements in the virtual environment. Subjects score statements by marking one of seven responses on a 7 step Likert scale that best reflect their feelings, ranging from *strongly disagree* to *strongly agree*.

The statements are related to the subject's perception of the fan as a part of the environment (e.g. *The wind originating from the fan added realism to the visuals representing wind the visual part of the environment*), the perception of wind through visual elements in the environment (*The wind appearing in the visual part of the environment, increased during the cycling trip.),* the perception of wind through the fan (*The wind force originating from the fan, changed during the trip*), the perceived level of coherency of the different channels (*The two wind sources (visual and haptic) corresponded in terms of wind force during the whole trip*) and a reflection of the subject's own cycling behaviour (*My cycling behaviour was affected by a change in wind conditions that occurred during the trip*).

When the participant finished the questionnaire, a semi-structured interview was conducted and recorded. During the interview, we asked participants to clarify some of their responses on the statements.

3.6.3 Immersive tendencies questionnaire

After evaluating the experience of the cycling trip, a general immersive tendency questionnaire was filled in by the participant. Eighteen items (ITQ01-ITQ18) taken from the immersive tendency questionnaire of Witmer and Singer [41], were included. Subjects responded by marking 1 of 7 answers from a Likert scale. Examples of items:

ITQ02: How frequently do you get emotionally involved (angry, sad, or happy) in the news stories that you read or hear? (Responses range from *Never* to *Often).*

ITQ11: When watching sports, do you ever become so involved in the game that you react as if you were one of the players? (Responses range from Never to Often).

4 RESULTS

In this section, we start with describing results on participants' experience of the cycling task and their immersive tendencies before actual cycling data are reviewed. In this way, observations made on self-reported experience of the cycling trip, are considered while evaluating the actual change in behaviour during the cycling trip.

4.1 Subjects

Three of 33 trials were omitted from the analysis (one subject did not complete the experiment and cycling data of two other participants were corrupted because of failure of measurement tools). The resulting number of subjects is 30 (19-34 years old, M = 25, SD = 4, 12 females and 18 males, 20 Dutch, 2 Chinese, 1 German, 1 Czech, 1 Spanish, 1 Azerbaijani, 1 Kurdish / Turks, 1 Cypriot, 1 Greek, 1 Slovak). All participants have general cycling experience.

4.2 Feeling of presence and immersive tendencies

In the feeling of presence questionnaire and the immersive tendencies questionnaire, participants score items in the range strongly disagree – strongly agree (1-7). Responses for items that have a negative influence on the overall measure, are reversed by subtracting the given response from eight. To give an example, high scores for the statement "*How much did your experiences in the virtual environment seem consistent with your real-world experiences?*" positively affect overall feeling of presence and high scores for the statement "*How inconsistent or disconnected was the information coming from your various senses?*" have a negative effect, as defined by Witmer and Singer [40]. Therefore, the score on the latter example should be reversed. Scores to each presence measure were summed across questions and divided by the total amount of questions to find scores on feeling of presence (FPQ scores, 8 items) and immersive tendencies (ITQ scores, 18 items). A final score of 1 corresponds with low feeling of presence (for FPQ) / low immersive tendencies (for ITQ), and a score of 7 corresponding to high feeling of presence (FPQ) / high immersive tendencies (ITQ).

The mean FPQ score found was 4.56 (N = 30, SD = 0.82). A Student's t-test was conducted to compare FPQ scores of subjects starting in the weak wind condition (N = 16, M = 4.48, SD = 0. 083) and FPQ scores of subjects starting in the strong wind condition (N = 14, M = 4.65, SD = 0.83). No significant differences were found; t = -0.57, df = 28, p = 0.57. Through this we conclude that the order in which the different wind conditions were presented to the subject during the cycling task, did not affect subject's feeling of presence. Immersive tendency scores of subject 17 were omitted because results were incomplete due to procedural failure. The mean ITQ score found was 4.08 (N = 29, SD = 0.73).

Because a person's immersive tendencies are a predictor of its feeling of presence in a virtual environment [40], we expect FPQ scores to be correlated with ITQ scores following the example of other researchers in [42]. We test the validity of the adapted questionnaires used to measure ITQ and FPQ, by evaluating the relationship between level of presence scores and immersive tendencies. We applied a Person correlation, which showed a positive significant correlation for the relationship between ITQ and IPQ of 0.50 (t = 2.86, df = 25, p-value = 0.008). From the scores used in this correlation, two participants were excluded. The ratio between their FPQ scores and ITQ scores were identified as outliers because they fell outside the lower/upper quartile minus/plus 1.5 times the interquartile. The mean ratio (FPQ / ITQ) was 1.14 (SD = 0.27) and ratios of the excluded participants were 0.58 and 2.07. Including participant 15, weakens the correlation to r = 0.43; t = 2.41, df = 26, p-value = 0.023, also including participant 34 breaks the significance. The plot in Fig. 6, shows ITQ scores against FPQ scores for each participant.

Non-correlating scores for subject's immersive tendencies in general (ITW), and their feeling of presence during this specific experiment (FPQ), could be a reason to review the questions chosen in the feeling of presence during the experiment. However, in the current situation we believe the measures are valid.

There is a significant difference in the ITQ scores of subjects starting in the weak wind condition (M = 4.36, SD = 0.73) and in the strong wind condition (M = 3.79, SD = 0.62); t = 12.25, df = 27, p-value = 0.03.

Drawing from this, it seems that an uneven distribution of participants with either high or low immersive tendencies existed over the two groups Although this difference is not reflected in the FPQ scores and there is a correlation between FPQ and ITQ scores, we feel it is worth noting that participants in the strong-wind first group, may have had a lower feeling of presence during the cycling task, because they have lower immersive tendencies in general.

While the two questionnaires are intended to measure subjective qualities via self-report, we cannot completely rely on the comparison of scores between different subjects. First because the interpretation of questions may not be uniform between participants and second because the interpretation of the range of possible responses on the answer scale, may differ between participants. This problem has already been addressed specifically for presence questionnaires as the Witmer and Singer questionnaires by several researchers (e.g. [43]).

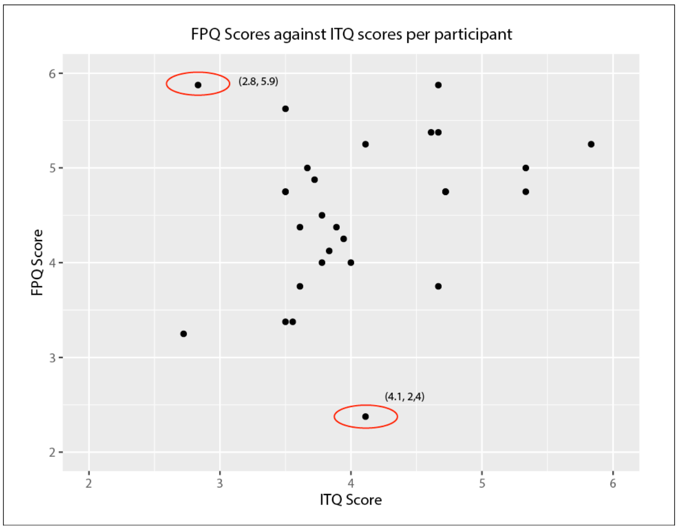

Fig. 6. Scatterplot of FPQ scores against ITQ scores with the two outliers marked.

To see whether a potential difference in immersive tendencies between the two groups (weak wind first and strong wind first) is also reflected in participant's experience of the cycling trip, we will compare the two groups in more depth when we look at results on participant's experience of specific elements in the environment in section 4.3. In section 4.4, we look into actual cycling behaviour of participants and also consider relations between feeling of presence and cycling behaviour.

4.3 Specific perceptual experience

Statements presented to the subjects after the cycling trip were specifically designed for the current study. An overview of the statements presented can be found in table I. For some statements, results from multiple different statements of the original 14 statements have been combined as they were aimed at measuring the same elements of subject's experience, but were formulated in a different way. For example, we presented both groups with 2 different statements on changes in visual wind. They subsequently state that wind increased or decreased. In table I, these statements are all summarized by S3. Results on statements are organized per topic and accompanied by relevant results collected during the semi-structured interviews that followed the questionnaire, because both the statement and interview questions aim to evaluate participant's perception of specific elements in the environment. Interview questions were more explorative and provide starting points for the discussion. Statements require a response on a 7-point scale, on where a score of 1 means a strong disagreement and a 7 a strong agreement. We will describe our results as disagreements when they fall below the middle answer of 4 and as agreements when they lie above 4. Relevant variations within the 1-3 or the 5-7 agreement range will be noted as well.

Table I. *Overview of statements reviewed and topics they relate to*

Statement		Topic (section)
S1	In general, there is a difference between my experience of the first and that of the second half of the trip.	Attention to visual elements and feeling of presence over time (4.3.1)
S2	The wind appearing in the visual part of the environment, changed during the trip.	Experience of changes in wind visual and haptic wind conditions (4.3.2)
S3	The wind appearing in the visual part of the environment, increased during the trip.	
S4	The wind force originating from the fan, changed during the trip.	
S5	The wind originating from the fan, added realism to the visuals representing wind in the visual part of the environment.	The role of the fan as part of the environment (4.3.3)
S6	The wind originating from the fan, distracted me from being involved in the environment.	
S7	During the whole trip, I felt that the different channels that were part of the virtual environment, formed a coherent whole.	Awareness of actual incongruency and perceived incongruency (4.3.4)
S8	The two wind sources (visual and haptic) corresponded in terms of wind force during the whole trip.	
S9	My cycling behaviour was affected by a change in wind conditions that occurs during the trip	Perceived change in cycling behaviour and resistance (4.3.5)

Used questions during the interview depended on participants' responses on the statements. We for example asked the following if a participant stated that he or she noticed a change in the visual wind conditions: *"You agreed that the wind force appearing in the visual part of the environment changed during the trip. Can you elaborate on this?"* and *"Can you specify what elements in the environment you saw, made you have this experience?"* If a participant stated he thought his cycling behaviour was affected by a change in wind conditions, we asked: *"In what way do you think the change in wind conditions affected your cycling behaviour?"* We always asked what participants thought of the fan as a part of the virtual environment. Besides these questions, participants often started elaborating on other parts of their experience by themselves.

In existing research, a distinction is made between 'level of immersion' and 'feeling of presence', in where immersion refers to an objective quality of a system and feeling of presence to the subjective sense of being in the virtual environment [44]. In the discussion of the interview results, we will use the terms 'immersion' as well as 'presence' to refer to the subjective feeling of presence, because subjects often used 'the degree to which they felt immersed' rather than 'the degree to which they felt present' in the environment while they were talking out their subjective experience.

4.3.1 Attention to visual elements and feeling of presence over time

During the interview, almost all subjects spontaneously discussed the quality of their experience in terms of the degree of enjoyment and / or realism, right at the beginning of the interview or at the end when they were asked if they had any more notes to make on their experience. Some subjects thought the cycling trip was boring and others were enthusiastic about it. Boredom was mostly attributed to the repetitive character of the environment, these people at some point started to question their progress in the entire task. Enthusiastic reactions consist of surprise about the realism of their experience and the added value of the fan as part of the environment, a relaxation effect due to the repetitive nature of the task, the fact that the task reminded them of their youth and the feeling of achieving something and making progress.

S1: *73% of the participants agreed that there was a difference between their experience of the first half of the cycling trip and that of the second half (agreement > 4). 20% did not agree with this and 6.67% marked the middle answer.*

Most of the subjects, related their response to S1 to an experience of a change in the visual stimuli representing a change in wind conditions. However, about half of the participants, not specifically part of one of the groups, also mentioned their feeling of being immersed in the environment increased during the task. A few thereby reported they did not notice the details in the environment at first, but started to recognize more details towards the end. Three people also said the wind from the fan became more realistic over time and this helped them to recognize the wind in the visual part of the experience. One subject told the opposite happened, as he was *"losing his feeling towards the end of the task"*.

With regards to the general experience of visual elements, some subjects thought they were to be questioned about hidden elements in the environment, because we told them the study was about 'situational awareness' during the experimental instructions. Therefore, they reported, they started inspecting the horizon and the trees to see if something notable came by that they might be questioned about. Also, multiple subjects reported they were trying to find out if all trees that were standing along the cycle path were the same or different. We chose to tell people the study was about situational awareness so that people would focus on the environment. This goal seems to be reached for most of the subjects. One subject told he experienced he had the tendency to start looking elsewhere after a while. Also, one subject, reported that he did not really look closely at elements and therefore was not completely sure about his answers in the questionnaire, but did feel very immersed in the environment.

An unexpected outcome was that 3 subjects told the cycling trip reminded them of the time when they were still in high school and daily had to take a road similar to the one they just cycled on in the virtual environment. They reported they had nostalgic feelings during the task.

4.3.2 Experience of changes in wind visual and haptic wind conditions

S2: *Most of the participants (73%) correctly perceived a change in the wind conditions in the visual part of the environment (agreement > 4). 43.33% of the participants strongly agreed that there was a change. 13.33% did not notice a change and 13.33% marked the middle answer.*

S3weak: *Of the participants starting in the weak wind condition (N = 16), 81.25% agreed that the wind appearing in the visual part in the environment increased during the trip (agreement > 4; 43.75% marked they strongly agree, with an agreement of 7). 12.50% did not agree (agreement < 4) and 6.25% marked the middle answer. No participants marked they strongly disagreed.*

S3strong: *On the statement if wind appearing in the visual environment increased during the cycling trip, 50% of participants in the strong wind first group, disagreed (agreement < 4), against a 42.86% agreement (agreement 5-6). 7.14% marked the middle answer.*

S4: *26.67% of the participants thought the wind force originating from the fan, changed during the trip (agreement > 4) but 33% was sure the wind force originating from the fan did not change (agreement = 7). 23.3% of the participants marked an agreement of 5 or 6 and 16.67% marked the middle answer.*

Most participants experienced a change in wind conditions occurring the visual part of the environment. We can conclude that participants in the weak wind first condition were aware of the change in wind conditions and its direction (81% agreed there was an increase in ***S3weak***).

We would expect to find opposite results for participants who started in the strong wind condition, namely that participants agree there was a decrease in wind. However as reported, results are more spread here (only 50% disagreement < 4 in ***S3strong***). This may have been caused by the fact that subjects in the strong wind condition show lower immersive tendency scores than subjects in the weak wind first condition (as reported in section 4.2) However, as no differences were found in FPQ scores between the two groups, we are not sure of this. Another possible reason is the fact that subjects reported to become more immersed overtime, which could have led to a higher specific attention to visual elements in the second part of the experience. They may not have noticed the visual cues of wind in the first half of the trip.

A more speculative explanation concerns the visibility of wind cues in the designed strong condition. A few subjects reported they could not see the end of the road because of the fog. They may have focused mostly on the road in front of them and not on the trees alongside the road, when the density of fog was high (in the strong wind condition). Furthermore, when we asked what elements in the visual part of the environment, made subjects think wind conditions were changing, one subject reported he did not see the change in the density of fog flowing by as a change in wind conditions. This was however contradicted by most of the subjects who spontaneously reported the amount of fog flowing by as an indication of a change in wind force as well as the change in movements of the trees and the ambience of the sky.

4.3.3 The role of the fan as part of the environment

S5. *57% percent of the participants felt that the wind originating from the fan, added realism to the visuals representing wind in the environment, while 27.67% of the participants did not agree (agreement < 4) and 16.67% marked the middle answer.*

S6. *10% of the participants felt that the wind originating from the fan distracted them from being involved in the experience (agreement > 4). 83.3% did not agree with this (agreement < 4) and 6.67% marked the middle answer.*

Most people were positive about the value of the fan: it made the experience more realistic and it helped them to become immersed in the environment. During the interview, some subjects mentioned that initially they thought of the fan as a separate object and were a bit distracted by it, but later the wind originating from it became more real. One participant mentioned mention he felt the wind was unnatural, because it was not reflected in actual force that one should perform to cycle. Multiple subjects also mentioned that the wind from the fan did not feel very natural because of its constant speed.

4.3.4 Awareness of actual incongruency and perceived incongruency

S7. *Most of the participants (73.3%) felt that the different channels that were part of the environment formed a coherent whole (agreement > 4). With 'different channels we mean: "The visual part: the field you cycled in, the haptic part: the wind presented by the fan. You and the bicycle you cycled as part of the environment," as was stated on the questionnaire form. However, only 36.67% of the participants said they were not aware of the different channels most of the time (agreement > 4), against 43.3% who did not agree with that (20% marked the middle answer).*

S8. *46.67% of the participants did think that the two wind sources (visual and haptic) corresponded in terms of wind source during the whole trip (20% even marked they strongly disagreed). 33.3% did agree (agreement > 4) and 30% marked the middle answer. This is in line with another statement where 46.7% of the participants stated they felt that the wind originating from the fan did not correspond with their visual experience of wind.*

People were quite divided in whether they perceived the two wind sources as one whole. Most people were aware of the actual incongruency of the visual and haptic cues, but some of them reported that despite their awareness of the actual incongruency, they still experienced the two wind sources as one whole. Some reported that the two wind sources became one whole at some point when they were further in the task and others reported that their feeling shifted between congruency and incongruency all the time. The most important note given by multiple subjects on what was incongruent about the two sources, was not so much about the actual difference in visually and haptic perceived wind force, but about the consistency of the haptic cues against the dynamic nature of the visual cues in the environment, that suggested a gustier wind condition.

4.3.5 Perceived change in cycling behaviour and resistance

S9: *53.33% of the subjects think that their cycling behaviour was affected by a change in wind conditions that occurred during the trip (agreement > 4, but the weight is on agreement on 5 and 6, only 3 people marked they strongly agreed). 40% of the participants did not agree (agreement < 4) and 3.33% marked the middle answer.*

16 subjects reported that the perceived change in their own cycling behaviour had something to do with the change in wind conditions. They saw the change in behaviour as a change in their cycling effort or a change in their cycling speed. Some were aware of the difference between cycling speed and effort, as they for example mentioned they felt like they increased effort but were not sure if this resulted in a higher speed, one comment: *"I had to give more effort when there was more wind, I had the feeling I started to cycle slower"*. A second group mentioned they at some point realized their speed had changed but thought this was caused by a change in resistance in the bicycle as this, so their speed changed, while the amount of effort stayed the same. Others just talked about the fact that they increased speed, but did not distinguish between whether this was caused by their own behavior of increasing effort, or by an external factor. Not all subjects experienced a change in their cycling behaviour when the winds changed, but just reported they *"cycled faster because there was more wind"*. Participants in the strong wind condition reported that they started cycling faster because of the wind, but did not all mentioned they started to cycle slower again when the wind laid down. Three subjects reported they felt the tendency to start to cycle faster but were conscious about that right away and tried not to do it because of that. They were not sure if this could still have influenced their speed.

One participant that thought he cycled faster when there was more wind, also mentioned he was tending to dodge the fog clouds that were approaching him by slightly moving his upper body to the right and left side. He on the other hand also said his speed could also have been decreased in the strong wind condition, because he could not see the end of the road. 14 participants thought there were cycling faster in the strong wind condition. A few reported that the change in cycling behaviour happened at the same time as the change in wind conditions, this in some way suggest a relation between the two factors. Others literally gave the change of wind conditions as a reason for their change in cycling behaviour. Quite a few participants spontaneously reported it as a natural effect, while they did not have any knowledge about our hypothesis. They for example said: *"(...) When wind force is increasing, you just have to cycle harder to keep going. (...)"* and *"(...) I think I increased speed because it felt as if I had to cycle harder because I had headwinds* (…)". *"(...) I was naturally trying to cycle harder as I always do when wind is blowing, I was trying to put more pressure on my knees. I did not think of whether I should do that. It happened naturally (...)."* Some people were consciously increasing speed, while others mentioned they discovered they were increasing effort.

Three participants from the weak wind first group, who self-reported they increased their cycling speed in the second part of the cycling trip, also reported that they thought the resistance of the bicycle increased as the amount of wind force increased. It could be possible that people experience an increase in resistance if they become tired over time and should put more effort to maintain their preferred pace, but it is interesting to note that also one participant who started in the strong wind condition, thought the resistance of the bicycle decreased in the second part of the cycling trip. This was the only subject thought it was cycling faster in the weak wind condition: *"it felt more comfortable when the wind was gone, therefore I cycled faster"*.

Besides the change of wind conditions, a few people also mentioned that they felt that the environment appeared threatening in the strong wind condition and this made them wanting to be home faster. One subject for example said: "It was very spooky at some point because there was nothing around me. This became more serious over time and it felt like the weather is changing to the worse, like a tornado was coming." For these people, not so much the current weather conditions, but the expected future weather conditions may have caused participants to change their cycling behaviour.

Another participant mentioned she was not sure whether she increased speed or if she felt like she did because the amount of wind originating from the fan increased over time.

4.4 Cycling data

In this section, we start to look at the actual cycling data. We take into account some of the results of the perceptual experience of subjects directly in our analysis. After explaining the data collection and preparation process (4.4.1), we start with looking at absolute changes in mean wheel rotations duration per group and per condition (4.4.2). After, we look at the spread of relative change (4.4.3) and the relation between change in mean wheel rotation duration and feeling of presence (4.4.4). We end by looking at the slope mean wheel rotations during each cycling phase per group.

4.4.1 Preprocessing of cycling data

Participants were asked to cycle for 1 kilometer. The wheel circumference was 2.125 meters, so this corresponds to completing 471 wheel rotations ($1000 / 2.125 \approx 471$) which is 236 ($471 / 2 \approx 236$) rotations per condition. A dataset with the duration of each wheel rotation made during the cycling task was outputted by the VE application, a csv file was then created via C#.

Outliers in wheel rotation duration (WRD) were expected because high speeds or abrupt sideward forces applied to the back part of the bicycle could lead to a failure of the wheel rotation detection mechanism that was created using a reed switch. Two types of outliers appear: when wheel rotations are missed, this causes the data to show unexpected high WRD's. In contradiction, when the reed switch accidentally switches 2 times in one actual wheel rotation, very low rotation durations are found. Outliers were removed by hand, by evaluating plots of each subject's WRD over time.

Only outliers were excluded that were clearly failures of the rotation detection mechanism (in that case, a single very high WRD is found or a single very low WRD is found) that is surrounded by regular values. In total 125 outliers were removed. 75 were of a positive nature (they laid in the high value range due to failure of detection) and 50 were of a negative nature (the laid in the low value range due to a double register during one wheel rotation). As an example, we show what outliers were removed for participant 29 in Fig. 7, that contains a graph of the non-adapted WRD (msec.) per cycle number.

After removing outliers, the last 200 cycles of the first phase and the first 200 cycles of the second phase are used for the final analysis. As there was some time between the moment the experimenter logged the moment the subject mentioned he or she found a comfortable position and the experimenter had left the experimental area, choosing to only use the final 200 cycles of the first condition lead to the exclusion of a short amount of wheel rotation registers that are assumed to be rotations made in a period the subject was still taking time to become immersed. In the plot in Fig. 7, labels show what values are used for the final analysis.

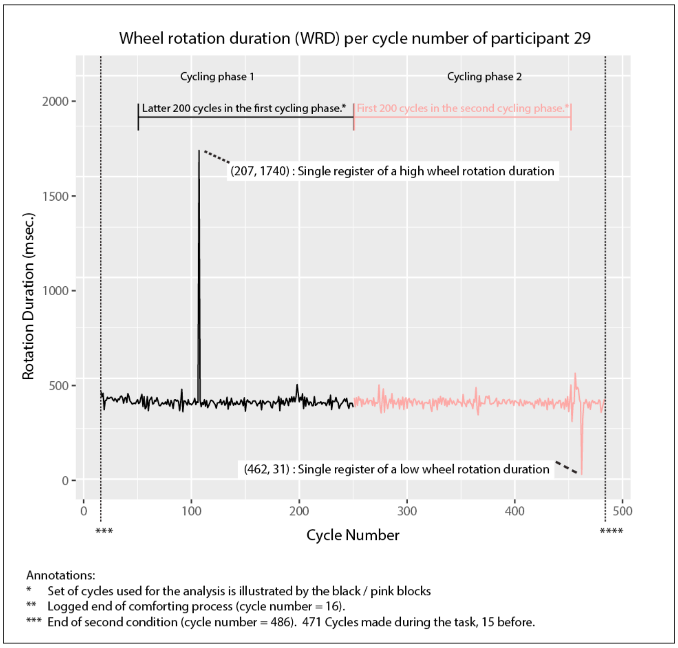

Fig. 7. Graph of the non-adapted WRD (msec.) over time for all cycles measured in the first wind condition (black line) and in the second wind condition (pink line) per cycle number for participant 17. The WRD measured for cycle number 297 is defined as an outlier, because of the high value (901). Cycles / rotations used for the final analysis are defined by the width of the black / pink block.

Cycle data were processed in R to summarize the most important specifications of each participants' cycling behaviour. We start with looking the mean wheel rotation duration, measured in milliseconds (mean WRD) per condition and per group, in where groups correspond to the order in which the conditions were presented: there is a weak-wind first group and a high-wind first group.

To understand how participants behaviour changed, an explanation of what a 'wheel rotation duration in msec.' means, is preferred: when the mean WRD of the second phase of the cycling trip, decreased compared to the first phase of the cycling trip, this means the mean cycling speed in the second half of the task was higher than in the first half, as participants took less time to complete a full wheel cycle and more rotations are made in the same amount of time. In the rest of the paper, we will either use the notation 'wheel rotation duration' or the abbreviation 'WRD'. When 'cycling phase' is used, we refer to either the first half of the cycling trip or the second half of the cycling trip.

4.4.2 Absolute differences in mean WRD

No significant differences are found when we conduct a paired t-test test (N = 30) to compare the WRD during the weak wind condition (M = 442, SD = 97) with the WRD in the strong condition, conditions (M = 440, SD = 90), independent from the order of exposure to the conditions; t = -0.31, df = 29, p-value = 0.76

If we consider the order in which conditions are presented, we see that significant differences exist between the WRD of the first half of the trip (M = 446.67, SD = 94) and the WRD of the second half of the trip (M = 435, SD = 93), independent of whether the second half was the weak wind or the strong wind condition if we look at all participants. The change is -11.3 msec. Results of per-group comparisons of mean WRD between the first half of the trip and the second half of the trip (phase 1 and phase 2) are shown in table II.

Subjects who started in the weak-first order, approximately show the same change in WRD (now: -11.75 msec.) between the first half of the trip (M = 426, SD = 98) and the second half of the trip (M = 414, SD = 88). For subjects starting in the strong wind condition, were mean WRD of the first phase was 471 (SD = 86) and for the second phase the mean WRD was 460 (SD = 95), the difference is not significant (change = -10.6 msec.).

We see that independent of starting condition, a decrease in WRD in the second condition of the cycling task occurred. The fact whether WRD data are drawn from the first cycling phase or from the second cycling phase, seems to have a greater effect on mean WRD than the actual visual stimuli and therefore carryover effects should have occurred. As the change in duration is approximately the same for all groups

Table II. *Comparing mean WRD between cycling phases per group through paired t-tests*

Group	N	Cycling Phase		t	df	p-value	change
		Phase 1 WRD	***Phase 2 WRD***				
		M (SD)	***M (SD)***				
All	30	446 (94)	435 (93)	3.09	29	0.004*	-11.23
Weak wind first	16	426 (98)	414 (88)	2.32	15	0.035*	-11.75
Strong wind first	14	471 (86)	460 (95)	1.97	13	0.07	-10.64

* Significant difference in mean WRD between first and second cycling phase

(All , N = 30: - 11.3 msec., weak wind first, N = 16: -11.75 msec., strong wind first, N = 14: -10.6 msec. (not significant)) we use the mean difference of -11.22 (mean difference = ((-11.3) + (-11.75) + (-10.6)) / 3) to correct the mean WRD for subjects in all orders (N = 30) by subtracting 11.22 from the mean WRD of each participant in the first phase. When we again evaluate the difference between the mean WRD (M = 436 msec., SD = 98 msec., corrected) during the weak wind condition and the mean WRD in the strong wind condition (M = 435, SD = 89, corrected), we do not see any significant differences yet: t = -0.17415, df = 29, p-value = 0.863.

4.4.3 Spread in change of mean WRD

The spread in participants' mean WRD (IQR Mean WRD independent of cycling phase = 392 – 489, N = 30) in combination with the knowledge that it seems that overall the WRD decreased in the second half of the trip, motivates us to look at relative changes in mean wheel rotations to see if subjects starting in one of the conditions, have a relatively greater or smaller change in WRD than participants in the other condition. The change in mean WRD in the second half of the trip, relative to the mean WRD in the first half of the trip (((Mean phase 1 – Mean phase 2) / Mean phase 1 * 100), are thus compared between the two groups.

By inspecting the boxplots of this relative change grouped per starting condition (see Fig. 8), we see that the weight of values lies in the negative range (meaning the WRD decreased over time) but positive change is not excluded. For example, two distinctive high values of 9.43 msec. and 6.26 msec. exist in the relative change in WRD of participants in the weak wind first group. Spread of change in WRD is even higher for participants starting in the strong wind condition (IQR = 5.50) than for participants who started in the weak wind condition (IQR = 3.70). These informal observations show that the nature of relative change in WRD, is not consistent and the change in wheel rotation duration in the strong wind first group, is even less consistent than that from the weak wind first group.

It could be the case that some subjects increase their output power and some subjects decrease their output power, based on their motivation: keeping the same speed or using a comfortable output power.

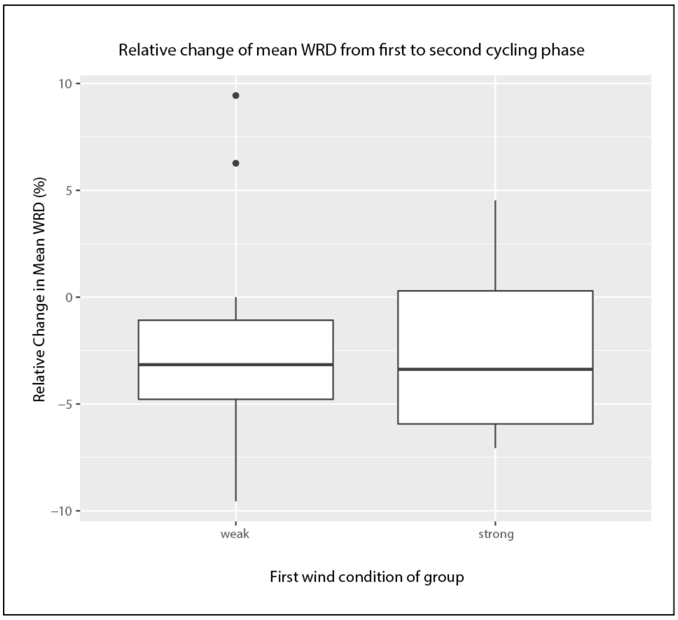

Fig. 8. Boxplot illustrating change in mean WRD relative to the WRD in the first half of the cycling trip, in percentages and displayed by group.

4.4.4 Relation between change in mean WRD and FPQ

We now look at the relationship between FPQ scores and relative change in WRD (N = 30). A correlation of -0.43 was found; t = -2.49, df = 28, p-value = 0.02. In Fig. 9, the relative change in WRD is plotted against the FPQ scores. As FPQ scores increase, relative change in wheel rotation duration between the first and the second half of the trip the decreases. This seems to indicate that the more subjects are involved in the cycling task, the bigger the increase in cycling speed is. A greater feeling of presence evokes more natural reactions to situations [45]. Therefore, we assume that a subject's cycling behaviour during the cycling task of someone with a higher feeling of presence corresponds more with its natural cycling behaviour than that it does for a subject with a lower feeling of presence.

Therefore, we examine cycling behaviour of a subset of the participants. We experimented with different threshold values for feeling of presence scores and found interesting results if only participants with an FPQ score larger than 4.8 are taken into account (N = 11). Relative change in WRD of participants starting in the weak wind condition (N = 7, M = -1.74 %, SD = 3.96 %) was significantly different form the relative change in WRP for participants in the strong first group (N = 4, M = -5.56%, SD = 1.06%); t = 2.4205, df = 7.3595, p-value = 0.04439. In the current situation, at the 4.8 threshold level, the change in WRD for subjects in the weak wind first condition is smaller (-1.74%) than subjects who started in the strong wind condition (-5.56%).

Now, it seems that subjects in the strong wind group relatively cycled even faster in the second half, than subjects in the weak wind first group.

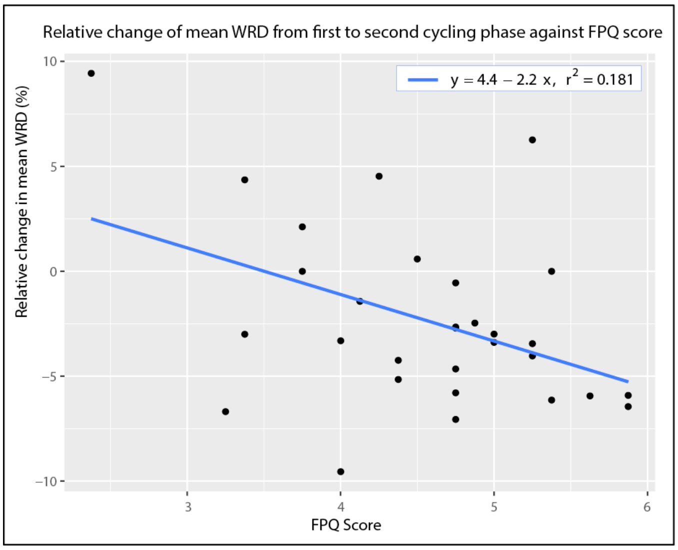

Fig. 9. Relation between relative change in WRD against FPQ scores.

This is an unexpected outcome, as we expected people cycle slower in the weak wind condition than in the strong wind condition. These results are hard to interpret at the moment, because of the arbitrary nature of the FPQ score threshold value of 4.8. When increasing the threshold to any value in the range 4.8 – 7.0, the difference does not occur ($p > 0.05$). However, if larger sample sizes would be available, one could examine whether there is a certain threshold of FPQ, above which a consistent difference in relative change of WRD between weak wind first and strong wind first subjects exists.

4.4.5 Between-subjects comparison of rate of change in WRD per cycling phase

As earlier described, there seems to be an overall tendency of cycling faster in the second cycling phase, independent of the condition of the second half. However, there was no significant evidence for this change for subjects in the strong wind first group. As quite some subjects reported they felt their cycling behaviour was affected by a change in wind conditions either because of its threatening character or because of their motivation to keep their speed, it could be the case that already in the first cycling phase, subjects in this group started to cycle faster while remaining this speed or even continuing the increase in the second cycling phase. This would lead to lower relative change in mean WRD between the first and the second cycle phase compared to subjects who only started to cycle faster in the second phase. So, in this case, not so much the change in wind conditions affected cycling behavior, but the initial wind condition that set the overall ambience did. As also only 50% of the subjects in the strong wind condition noticed that the wind decreased in the second half of the trip, it would make sense to look at the rate of change in cycling speed per condition and per cycling phase. As this is actually a between subject comparison, it is hard to interpret these results because we cannot be sure whether this initial explorative result and potential other more precise findings should be attributed to exposure to the first or the second condition or to both. An attempt has been made to inspire future research designs.

We calculated the coefficients of the regression lines for each participants' wheel rotation duration over time per cycling phase (by making use of the regression function lm() in R (lm(WRD ~ cycle.number))). So, in this case, 'mean rate of change', is the slope of the regression line of a subject's wheel rotation duration over time. In table III, an overview of the amounts of positive and negative slopes is given. In table IV, the slopes between the two groups are compared for each cycling phase. As we can see, the slopes in the first phase are almost the same for the two groups. However, in the second cycling phase, a significant difference exists between the two groups. The mean slope of the weak wind first group is -0.42 (SD = 0.67) and the mean for the strong wind first group is -1.07 (SD = 0.57); p = 0.008.

Table III *Nature of acceleration per group and per cycling phase*

Cycling phase	Nature of slope	Groups	
		Weak wind first (N = 16)	***Strong wind first (N = 14)***
1	Positive	6	4
	Negative	10	10
2	Positive	3	1
	Negative	13	13

Table IV *Comparing slope of change in wheel rotation duration between cycling phases per group through students' t-tests*

Variable	Groups		t	df	p-value
	Weak wind first (N = 16)	***Strong wind first (N = 14)***			
	M (SD)	***M (SD)***			
Slope in phase 1	-0.52 (1.02)	-0.53 (0.78)	0.009	28	0.99
Slope in phase 2	-0.42 (0.67)	-1.07 (0.57)	2.84	28	0.008*

* Significant difference in rate of change in WRD between weak- and strong wind first group

This result shows that in the second cycling phase, subjects in the strong wind first condition have a faster decrease in wheel rotation duration rotation than subjects in the weak wind first condition. Interpretation can be done in several ways. If we assume the starting condition attributes more to the overall speed of decrease in wheel rotation duration than the second condition, because this sets the subject's state of mind and overall speed of decrease in WRD, we could conclude that strong visual cues of wind, decrease WRD faster than weak visual cues of wind, which corresponds to subjects' self-reported behavior of tending to starting to increase cycling speed in the strong wind condition. Because there is almost no difference in the speed in decrease in the first cycling phase between the two groups, this seems unlikely. This could be explained if we take into account that some subjects reported their feeling of presence increased during the task. Now, we attribute the change in speed of decrease of WRD to exposure in the latter phase of the task (and therefore weight lies on the second condition), because subjects were more involved at that time, and started to notice more details in the visual part of the environment. As in that period, subjects in the strong wind condition showed a higher speed of decrease of WRD, weak wind visuals would make subjects cycling speed increase more than strong wind visuals. This is in contradiction with subjects' self-reported behavior of how their cycling behaviour was affected.

5 DISCUSSION

In this research, we examined perception of incongruent multimodal cues of wind and the reflection of this in cycling behaviour. We will first discuss conclusions and implications of results gathered during the cycling task and the assessments of subject's experience of this, before discussing potential applications and evaluating the used methodology.

5.1 Perception of incongruent multimodal cues of wind

Most participants, were sure the wind originating from the fan did not change during the cycling task. They were consciously aware of the presence of incongruency in the presented information. However, some of them still reported they experienced the two wind sources as one whole and felt affected by the visual and haptic wind sources together. This is in line with earlier findings that showed that even when people are asked to pay attention to one of two sensory modalities and know irrelevant cues can be present, they are still affected by the irrelevant modality [26][5]. When we look purely at how subjects describe their overall experience during the interviews, rather than focusing on the statements about whether subjects experienced changes in either the visual or the haptic wind condition, we observed that people tend to try to combine information of different sources while they are aware of their contradictions. This could be an indication that especially in in a more natural situation where people are not consciously aware of potential incongruences, visual cues of wind affect haptic perception of wind.

Earlier research showed that visual perception often dominates other sensory modalities e.g. [25]. While it seems that interaction effects occurred for multiple participants, only a few subjects observed a change in haptic cues in the same direction as the change in visual cues, when only the visual cues changed. Therefore, we can conclude that in the experiment, a more unconscious interaction between the senses may have taken place for only these participants. They were not aware of the incongruency and visual perception dominated haptic perception.

We instructed people to keep looking at the screen the whole time, but subjects did not have any other incentives to see the visual stimuli as more relevant than the haptic stimuli. Interestingly, most participants who were not convinced of congruency reported that *the wind coming from the fan, deviated from the wind they saw*, and not that *wind they saw on the screen, deviated from the wind they felt from the fan*, which indicates participants see the visual channel as their main reference channel. They focus on the stimuli appearing on the screen as the basic channel.

5.2 Cycling behaviour and perception of cycling behaviour

Overall, subjects' mean WRD decreased between the first half of the cycling trip and the second half of the cycling trip. Furthermore, relative change in mean WRD decreases as subject's scores on feeling of presence are higher. If we compare the second with the first cycling phase, independent of starting conditions, we do not see expected effects of changes in visual cues of wind. Change in wheel rotation duration between the first and the second half of the trip therefore does not purely relate to a change in wind conditions. So, we cannot say anything about whether the found potential interactions between the senses in perceived wind conditions are reflected in human behaviour.

Either learning effects or fatigue effects have occurred. With fatigue effects, we mainly mean subject boredom, which could have led to the phenomenon of subjects starting to cycle faster at some point during the cycling trip, to be finished with the task earlier. This is reasonable because some of the subjects reported they indeed thought the cycling trip was not that interesting anymore at some point during the trip. This was endorsed by the fact that subjects did not have any idea about the progress they made already. Effects could also have been caused by getting used to the bicycle and the cycling activity on itself, which suggests the existence of a learning effect.

If we consider that subjects self-reported they started cycling faster when visual wind became stronger it could be that subjects in the strong wind first group started cycling faster earlier than subjects in the weak wind first group, because they were exposed to strong wind earlier. Also, subjects in the strong wind first group, did not experience a change in wind conditions as often as subjects in the weak wind condition. It could therefore be the case, that the starting wind condition sets the trend for the overall speed and possible increase and decrease in speed that can still be made in the remaining part of the cycling task. The combination with potential fatigue and learning effects, make the current results hard to interpret and we cannot say whether changes in cycling speed are due to changes in visual cues of wind and in what way they might have been affected. Carryover effects are too large. Therefore, we will review the experimental design in the closure of the discussion (5.4).

One participant thought she had an illusion of acceleration because the wind originating from the fan increased during the task (while in fact the wind did not change). This is interesting because it is known that wind perception contributes to perception of speed [2]. Some subjects thought the wind from the fan changed and others thought they might have been influenced by their visual perception of change in wind force. In both cases, an experience of change in actual wind, could have affected subject's perception of speed.

Besides visual cues, change in physical properties during the task, such as body temperature and the amount of perspiration, could in their turn have increased perceived strength of wind, as we expect subject's body temperature is increasing while exercising. This could have increased the perception of speed even more as perspiration increased during the task, when time passed by and wind is perceived as colder when perspiration increases [46].

We now combine the claim of perception of wind as an influential factor on perceived speed, a potentially increasing body temperature during the task leading to an increasing perception of wind force and the knowledge that subjects thought they increased their cycling speed. This leads to the idea that a possible illusion of acceleration could have even been stronger for participants in the weak wind first group than for participants in the strong wind first group. In the weak wind first group the nature in change in perceived actual wind and perceived visual wind correspond (they both become stronger) while in the strong wind first group, the nature of these changes is different: the visually perceived wind becomes weaker, while the haptic perceived wind may become stronger (as people starting to sweat more at some point during the trip). This could also explain why participants in the strong wind condition did not experience a decrease in visually perceived wind as often as participants in the weak wind first group experiences an increase in the amount of wind.

None of the subjects mentioned they experienced more actual wind over time because they started sweating, but we believe this is an important feature to take into account in future experiments.

Regarding the general effect of incongruent multimodal cues of wind on cycling behaviour, we believe the most meaningful finding in the current study, is that subjects self-reported they tended to increase cycling effort and therefore speed because of the strong wind they were exposed to. They mentioned they thought their cycling behaviour was affected by a change in wind conditions ($N = 16/30$). Except one, most of them thought they increased speed during the strong wind condition. A few additional subjects ($N = 3$) reported they felt the tendency to increase speed when wind force was growing, but discovered that right away and tried not to do it. It could have been a form self-justification, if the increase in cycling speed was caused by other factors discussed (known or unknown to the subjects). However, the fact that all of these subjects, except one (so $N = 18$), related a stronger wind to a higher cycling speed, without the instructions and statements presented before the interview suggesting anything about in what way cycling behaviour could have been affected, demonstrates that relations between exposure to visual cues of wind, and cycling behaviour exist in such a way that people tend to increase their cycling effort when wind seems to become stronger.

It could be interesting to devote future research to perception of acceleration in this direction and also take into account effects of perspiration over time on perceived wind force. Furthermore, to see whether the perception of acceleration in cycling behaviour corresponds with actual behaviour, participants could be divided in two groups. In table III we saw that rate of change in mean WRD was negative for most subjects, but a distinction could be made between subjects that start to cycle slower and subjects that start to cycle faster.

5.3 *Application of incongruent multimodal cues of wind*

From findings on the perceptual experiences of participants, we derive that providing multimodal incongruent cues of wind, have some potential applications, whether or not their perception is reflected in behaviour. Most subjects thought the fan added realism to the experience and some reported it helped them to become immersed in the environment. This is in line with earlier findings that providing actual wind through a wind display in virtual environments, increases user felt presence [17][18]. Subjects who were aware of the static nature of the wind originating from the fan and the incongruency of the two channels, often still reported that they experienced the wind condition as one coherent whole. Therefore, we believe that incongruent haptic and visual stimuli of wind, could be used in for example games to evoke a wide range of perceptual experiences of wind, by mainly focusing on the graphical representation of wind, without the need of a computationally heavy and physically complex wind display. To improve on the usage of such setups, it should be taken into account that the amount of realism the haptic stimulus in the current situation, increased over time. Therefore, an introduction period is preferred. Also, realism of the haptic wind force could be increased by adding some dynamics instead of just providing a constant flow of air. Although this was not preferred in the current experiment, because it would interfere with the effects of visual cues, a more dynamic wind force and real force feedback could be included. Visual and haptic provided wind cues do not have to correspond completely, but the degree of dynamicity should be increased, if visual cues suggest a gusty wind condition. Including actual force feedback of wind, that is applied to the bicycle would also increase the experience of realism.

5.4 *Using a virtual cycling task to study the reflection of multimodal processing in behaviour*

The use of a virtual cycling trip to study multimodal processing, had both interesting as well as limiting consequences. While interesting evidence was found on subject's perception of incongruent multimodal cues, the design of the cycling task itself, turned out not to be as convenient as expected.

5.4.1 *Presentation of stimuli*

Subjects were quite enthusiastic about the realism of their experience and most of them recognized the stimuli that were included to illustrate certain wind conditions in the way we intended. However, the existence of the fog and mainly the higher density it had in the strong wind condition, should be reviewed. The high density may affect participants cycling behaviour and perception of the environment in an unforeseen way. Subjects could have mainly been focusing on the road because they could not see what was approaching. This can result in subjects missing important elements occurring at the side of the rode. Interestingly, fog has been shown to increase speed in a virtual car driving simulation [47]. Despite only one participant mentioned he felt he started to cycle slower, also effects of fog on cycling speed and perceived cycling speed should be reviewed. The perception of virtual visual cues indicating the presence of wind, could be studied to reach higher levels of realism.

Some subjects were aware of the actual incongruency, but still reported they experienced the stimuli as one coherent whole. In the current study, this may have had a negative influence on the degree to which participants showed natural perception and behaviour because in real-life, we are not aware of the process of creating a coherent whole of multimodal stimuli [4], and some subjects were during the task.

To evoke more natural behaviour, we could try to improve participants' feeling of presence during the task. One way to do this, would be testing the same kind of cycling task with an increase in immersion of the virtual environment, for example by making use of a head mounted display. During development of the methodology, this idea was regarded because a head mounted display would negatively affect cutaneous wind sensation, but as it turned out most participants were aware of the incongruency of the two stimuli. Providing higher immersive environments, may push subject behaviour towards a higher level of reality. By excluding subjects from being able to see (HMD) and hear the physical wind device (sound could be added to the experience), we also believe subjects will be less focused on the fan as a separate part of the environment. Another idea would be to dim the lights in the room, as immersion increases in darker conditions [48].

5.4.2 Experimental Design of the cycling task

One of the main limitations in the current study is the application of the structure designed to present subjects with both the wind conditions. Because it turned out most subjects mean change in WRD increased and the amount of increase did not differ a lot between the two groups, it was hard to tell whether these changes were influenced by one of the two conditions. It would have been interesting to include a control condition, in where wind conditions in the two cycling phases are equal. As we now know that subjects, independent from condition, increase speed over time, we expect that also subjects in this proposed task will increase their cycling speed. Comparing the amount of change or rate of change of current conditions with this control condition, could reveal more about the role of changes in visual cues of wind.

If we assume this increase always occurs, a non-continuous presentation of the weak and strong wind conditions should be considered. In the current study, we chose to switch the visual wind condition half way because we could make sure subjects in that case enter the two conditions with the same psychological and physical intentions. However, using two separate tasks with resting time in between, is preferred because in that case, the two conditions do not depend on each other as they do now. In that situation, we still expect subjects to start to cycle faster over time, but we can then better compare the rate of change between two trials. Including a trial cycling task would help subjects getting used to the bicycle and prevent them being better at using it during the second presented condition (as is done in [39]). Another idea would be to present subjects with a longer task, which precedes a way longer introduction so subjects get used to the bicycle. However, in the latter proposal, the issue of boredom would still exist.

Also, during the interviews it turned out that not only the current wind condition, but also the expected weather condition that people got from looking at the environment, made them wanting to cycle faster. This is in line with earlier findings [8] that show that not so much actual perception of haptic cues but the expected haptic effort needed does affects the effort we give. However, in the current study, most subjects self-reported this behaviour, while in the study of Hershberger and Misceo, it was drawn from subjects' perception of weight. Therefore, we cannot state that the effect is the same. To find out more about this, it would be interesting to adopt the way stimuli were presented in [8]. In that case, not a continuous wind condition, but a very dynamic windy environment should be used. Haptic cues of wind also change and two conditions are included: visual cues that indicate a change in wind conditions appear right before haptic cues of wind change or haptic and visual cues of wind, change simultaneously.

5.4.3 Context and Task

In the cycling task, subjects were not told about the actual aims of the study. However, mentioning it was about 'situational awareness' motivated some subjects to closely inspect the visual elements occurring in the environment because they thought they would be questioned about it. As this would not happen during a real-life cycling trip, this has affected their perception towards the unnatural. Some subjects had associations with the activity of cycling home from school during their youth. This could have positively influenced the FPQ scores, because it may have helped them to relate the task to their real-world experiences. To solve this issue, the activity of the cycling task should have a clearer context for all participants. To overcome the issue of boredom, more concrete tasks could be included in the experiment. These tasks can or cannot be relevant for the subject of study. Important is, that these tasks do not have unknown effects on cycling speed. An idea would be for example, including a game like element, that does not entail any cycling performance.

If we want to study cycling behaviour in different wind conditions, we want to make sure participants react to cues of wind as they would normally do, while not taking too much attention on the task of cycling itself. Including concrete tasks as described above, may help to achieve this because they will become distracted by the measurements we are interested in.

5.4.4 Studying multimodal perception in context

One of the goals of the current study was to evaluate potential methods to study the reflection of multimodal processing in real-life like behaviour. The use of a plain cycling task, has some drawbacks still and adding a more concrete task for participants that would distract them from the activity of cycling, may help to evoke more natural behaviour in participants. A starting point in the research was to open a discussion of the level of control that one should strive for, to get real insights in the way multimodal processing affects our daily lives. We posed that using highly controlled experimental tasks, would not give insights in how multimodal processing affects our perception and behaviour in real-life. However, it turned out that the proposed method has potential for evaluation of subject's perception of the cycling task and environmental conditions, but the experimental task as well as the presentation of conditions, should be reviewed in future studies to be able to make more solid conclusions of how visual cues of wind affect cycling behaviour.

6 Conclusion

Effects of order and time in the cycling task are larger than possible effects of changing visual cues of wind in a situation where haptic and visual cues are incongruent. Perception of personal cycling behavior does support the hypothesis that cycling speed increases when visual cues indicating the presence of wind, are becoming stronger, but further methodological developments are required to be able to determine how interactions between the senses in perception of wind are reflected in actual behaviour. We propose a step back should be taken and review the level of control that is needed in an experiment on multimodal processing and the assumptions that have been made during the development of the methodology.

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