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Neuropsychological Aspects of Redirected Walking in Virtual Reality

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NEUROPSYCHOLOGICAL ASPECTS OF REDIRECTED WALKING IN VIRTUAL REALITY

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Summary

Locomotion through a virtual environment strongly increases the feeling of immersion. At the same time, real, unrestricted walking poses a serious problem to the maintenance of immersion. Specifically, the walls of the physical room pose the danger of collision. “Redirected walking” uses rotation of the virtual scenery to direct the user onto a curved walking trajectory in order to avoid physical obstacles. So far, there have only been limited efforts to study the perception and applicability of redirected walking. To address this gap, this project aimed at increasing the knowledge about redirection by investigating three central aspects of applied redirection. First, the detection thresholds of redirection and the drivers of the inter-subject variability in redirection sensitivity were investigated. Second, the relation between redirection and the feeling of agency was examined. And third, the possibility to predict future walking pathways of users to enhance redirection efficiency were tested by means of a spontaneous alternation paradigm. The investigation of these features represents a crucial next step in defining the potential, the limits and the psychological effects of redirected walking applications.

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PART I

GENERAL INTRODUCTION

1 Introduction

The present dissertation is the result of a collaborative, interdisciplinary research project. The collaboration was mainly triggered by the efforts of Prof. Andreas Kunz, who is the head of the ICVR group at the ETH Zurich. ICVR stands for Innovation Center for Virtual Reality and as the name suggests, the group investigates new trends in virtual reality (VR) systems and applications. Research about VR is firmly connected to the intended consumer of such systems, which is the human user. Therefore, questions about how humans perceive, tolerate and react to VR often take centre stage in VR studies. It was this emerging focus on human behaviour, which led Prof. Kunz to seek the contact with researchers of the psychological sciences. In Prof. Bigna Lenggenhager, at that time working as a post-doc researcher at the neuropsychology unit of the University Hospital of Zurich (USZ), he found a first collaborator. This contact quickly led to the acquaintance of Prof. Peter Brugger, who held the position of head of the neuropsychology unit. Subsequently, the triangle quickly submitted an SNF research grant, which included founding for two PhD positions. The two positions were filled by Anh Nguyen on the ICVR side and me on the USZ side.

Although the two fields differ substantially in their nature, VR research has repeatedly turned to psychology in the past (and vice versa). In fact, VR is a regularly used tool in psychological research today and the perception of VR, including its neural underpinnings, has been thoroughly investigated (see Jäncke, Cheetham and Baumgartner, 2009). One advantage of VR for psychology is that it allows participants to experience scenarios and stimuli in a controlled and realistic fashion. This makes it possible to test human behaviour under experimental conditions, which would be hard to simulate otherwise. In addition, psychologists have recognized VR’s potential for clinical applications. VR has been applied in what can be described as a virtual confrontational therapy approach, showing some success in the treatment of anxiety disorders such as fear of heights or phobia of spiders (Garcia-Palacios *et al.*, 2002; Freeman *et al.*, 2018). Furthermore, the possibility to experience a situation literally through the eyes of somebody else has raised the idea of modulating emotions and even ethical principles of users (Herrera *et al.*, 2018).

As outlined above, it is not uncommon in psychology to use the advantages associated with VR. However, in contrast to many conventional VR studies, the collaboration underlying this dissertation intended to benefit both fields, VR research and psychological research, in an equal manner. Thus, it was not the idea to use one field as a mere tool to gain knowledge in the other, but rather to have a simultaneous profit going in both directions.

The overarching theme of the collaboration was the principle of redirected walking, or redirection. Redirected walking is a generally rather unknown method (except of course in the VR community), which allows the manipulation of VR users' walking behaviour. As such, it represents a very attractive research object for psychology and VR research alike. The result of the collaboration was a thorough investigation into the perceptual characteristics, mechanics and potential improvements of redirected walking. What exactly constitutes the attractiveness of redirected walking and which research questions were targeted shall be described in the following sections. In this description special attention will be paid to how the psychological side of the equation applied itself in the collaborative effort. In addition, I would like to zoom in on some of the methodological details of the experiments, since a large part of my contribution was centred around them.

2 What is redirected walking?

As briefly hinted at in the introduction, redirected walking is a method in VR to manipulate the walking behaviour of users. In order to understand what exactly is meant by that and why it is relevant for VR applications, one has to begin with some background information. Today, the term VR is mostly associated with head mounted displays (HMDs). An HMD is essentially a small screen, which is strapped to the head so that it comes to rest in front of the eyes. The main innovation of such “video goggles”, is that they incorporate a range of sensors, which track the head movements of the person. Using these sensors, the presented virtual environment (VE) is made to react to the user’s head movements just like the physical environment does in reality. Thus, turning the head to the left for example results in the VE to move accordingly, allowing the user to inspect his/her virtual surroundings in a natural way. Being able to look around in the virtual world in such a fashion, gives a strong sense of being positioned inside the VE instead of merely looking at it from the outside. This sensation is generally referred to as feeling of immersion. Strong immersion is often regarded as the main goal of any VR application and has become somewhat of the holy grail in VR research. One unsolved problem of VR using HMDs, however, is the problem of locomotion. Users want to be able to move around in the presented virtual world. Early solutions made use of joysticks or hand-held controllers, which allowed locomotion via button press. Obviously, this is a rather poor approximation to real walking. More sophisticated devices, trying to mimic the feeling of real walking, were developed in the form of 360 degree treadmills (Souman *et al.*, 2011). The user is strapped in on these treadmills and can “walk” in any direction while staying physically on the spot. Often this is achieved by wearing special shoes, which slide back when taking a step in any direction. Although such treadmills and similar inventions are impressive feats of engineering, the sensation of using them unfortunately does not do justice to the sensation of real walking. The most natural approach to virtual locomotion is achieved by letting the user use real walking to navigate the VE. Using position tracking, the physical movements are simply transferred one to one into the virtual space. Thus, when a user takes a step in reality, the same step is also performed in the virtual world. This approach mimics the feeling of walking perfectly, since the user is indeed walking. However, there is a new problem associated with the approach. Since the presented VEs can be of large size in terms of spatial dimensions, a very large tracking space would be required. Normally, such a tracking space is not available, which makes the VE surpass the physical room. The size mismatch between the virtual and physical room, creates the danger of collisions with physical boundaries, i.e. the walls of the room. The danger of collisions is naturally amplified by the fact that the user is blind to the physical surroundings due to the HMD on his/her head.

Redirected walking is a software-based approach to the problem of physical boundaries (Razzaque, Kohn and Whitton, 2001). The working principle behind it is that physical movements are not transferred one to one to the virtual space. In general, there are three ways how physical movements can be distorted. First, a physical translation of the user can be turned into a shorter or longer virtual translation. This is referred to as a translational gain. Specifically, it could mean that a one meter step in the physical environment results for example in only half a meter step in the VE. The size of the translational gain determines the degree of distortion, so a passed distance can be shortened or elongated to any desired distance in the VE. The same manipulation method, but applied to rotations, is called a rotational gain. Using a rotational gain, a physical rotation of a given angle is turned into a smaller or larger rotation in the VE. The third type of redirection technique is referred to as a curvature gain and works in a slightly different way. A curvature gain induces a rotation of the VE around a moving user. Thus, when a user moves in any given direction, the whole virtual world starts rotating around him/her. While the user might not even notice the manipulated behaviour of the VE, he/she will automatically correct for the rotation by walking on a curved pathway (see Fig. 1). In the most extreme case one could imagine a user walking in a full circle physically, while virtually walking in a straight line through the VE. With a large enough room a user could walk infinitely far through a VE without ever hitting a physical wall. The most fascinating aspect of the three redirection methods is the fact that as long as the redirection gains stay below a certain intensity, users fail to notice the manipulation of their walking trajectory.

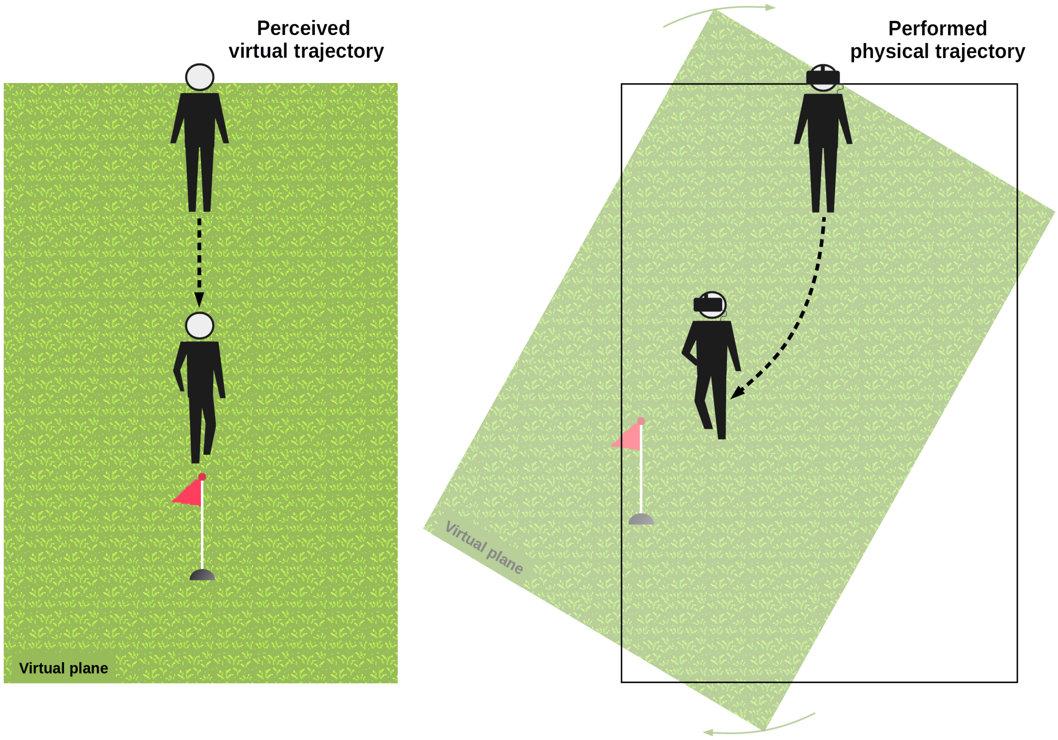


Fig. 1: Visual representation of redirected walking using a curvature gain. The perceived straight virtual trajectory (left) is turned into a curved physical trajectory through rotation of the virtual environment (right).

The intended application behind redirected walking is to use the three types of redirection gains, to guide users away from physical boundaries when exploring a VE by foot. This would enable users to explore much larger VEs than the available physical space, while preventing collisions with the room's walls. Ideally the pathway guiding and manipulating happens without the user noticing anything, so that the feeling of immersion is not disrupted. So far, redirected walking has only been used very scarcely in commercial applications (Martindale, 2015). It resides mainly in the research domain, where its application and effectiveness is steadily investigated and further developed. The most modern implementations of redirected walking are capable to apply redirection in an adaptive fashion, taking into account the user's location inside the physical and the virtual environment. Studies show, that the rate of resets due to a collision with physical boundaries can be significantly reduced using such redirection systems (Zmuda *et al.*, 2013; Hodgson, Bachmann and Thrash, 2014; Nescher, Huang and Kunz, 2014). Thus, the goal of preventing collisions and enabling the exploration of large VEs in confined spaces with redirection is theoretically feasible. In the course of this project we exclusively worked with curvature gains, no translational or rotational gains were studied. Therefore, from here on the term “redirected walking” usually refers to this specific type of manipulation.

2.1 (Neuro)psychology and redirected walking

The question remains how psychology, or in this project specifically neuropsychology, can assist the exploration of redirected walking. In the above description of redirected walking it should become apparent that redirection heavily relies on the way people process feedback of their walking behaviour. Furthermore, it seems that the key point of redirection is an elicited sensory mismatch between the visual feedback and the bodily feedback. When being redirected onto a curved pathway, the eyes are reporting a straight walking trajectory, which contrasts the bodily feedback of a curved trajectory. It is reasonable to suspect that the cause, why redirection can go unnoticed by users, is to be found in the way the brain handles the two conflicting feedback streams. Multisensory integration and action monitoring are frequently studied areas in psychology (Castiello, Paulignan and Jeannerod, 1991; Fourneret and Jeannerod, 1998; Bertin and Berthoz, 2004; Grace Gaerlan *et al.*, 2012). Thus, expertise from psychology could be helpful to gain a more in depth understanding of the working mechanisms underlying redirection. In turn, redirected walking offers an attractive opportunity for psychology to study action monitoring for the full body action of walking. Conventionally, such studies were restricted to goal-oriented hand or arm movements (Bock, 1992; Leube *et al.*, 2003). As will be shown throughout the dissertation, this is not the only point of exchange between the two involved fields in this project. In total, the project was composed of three main segments, each addressing a different aspect of redirected walking. In the following, the project’s focal points will be presented in more detail.

3 Redirection thresholds

Before investigating the inner workings of redirection, the project's goal was to take a more application-oriented look at redirection perception. As described above, the main appeal of redirection is that it goes unnoticed by the user. Having users not detect any mismatch between reality and the virtual world is important to not sabotage the feeling of immersion. However, the user is only fooled about his actual walking trajectory as long as the manipulation doesn't become to strong. The curvature gain intensity sets the radius of the curvature that a user is forced on. The unit of the curvature gain is the inverse of the curvature radius (1/m). Thus, the larger the curvature gain, the smaller the radius of the curved pathway becomes, which corresponds to a stronger manipulation. A fundamental question in the application of redirection is how strong a curvature gain can become, before a user notices the manipulation. This measurement is generally referred to as a redirection detection threshold (or short: Redirection threshold). Multiple research groups have published studies concerning redirection thresholds. In *2010, Steinicke et al.* ran an extensive user study to estimate the detection thresholds of translational, rotational and curvature gains. This initial push into the topic has been followed by studies, taking a more in depth look at redirection thresholds. Researchers have for example examined the effects of the VE complexity, cognitive load and walking speed on redirection thresholds (Neth *et al.*, 2012; Bruder, Lubos and Steinicke, 2015; Paludan *et al.*, 2016). Despite the available work on the topic, estimating redirection thresholds anew was relevant to the present project. For once, the used VR systems may differ between research groups and therefore redirection thresholds could vary as well.

In psychology there is an abundant literature on the topic of estimating detection thresholds. Specifically, the field of psychophysics is specialized on threshold measurement. Our goal was to apply basic psychophysical methods to the task of estimating redirection thresholds. Previous studies on redirection thresholds have made use of psychophysical methods as well. In our opinion, however, a deep dive into the psychophysical literature revealed, that the available methods were often not adequately implemented. One large part of realizing our redirection threshold study consisted of working out the details of the threshold estimation procedure. I would like to give a short summary of the issues involved with estimating redirection thresholds and how we attempted to solve them.

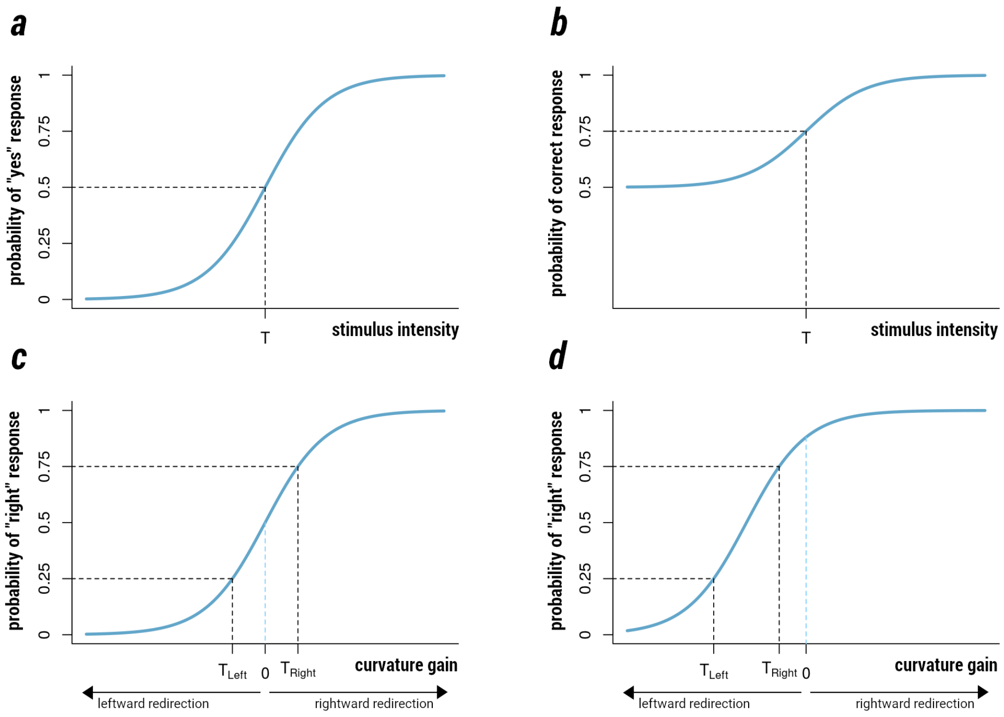


Fig. 2: Psychometric functions of different threshold estimation procedures. (a) shows the psychometric function of the classical "yes/no" approach. In (b) the corresponding function of the 2AFC approach is presented. (c) shows the commonly used "left/right" approach to estimate leftward and rightward redirection thresholds (curvature gain). In (d) the issue of subjective biases in the "left/right" approach is visualized. The detection threshold for rightward redirection has jumped the point of zero redirection and now lies on the side of leftward redirection.

The fundamental idea in psychophysics is that there is not an absolute threshold on the continuum of stimulus intensities. Thus, there is not an intensity below which the person will never detect the stimulus and above which the person will always detect the stimulus. Detecting a stimulus is rather modelled after a continuous probabilistic function. Classically, a psychometric function is used. The most basic threshold measurement is referred to as a constant stimuli Yes/No approach. In this approach, the participant is exposed to a range of stimulus intensities. In each exposure, he/she is asked whether the presented stimulus was perceived or not. Thus, the answer is always a "yes" or a "no". The associated shape of the psychometric function is shown in Fig. 2a For low stimulus intensities the probability of answering “yes” goes against zero. With increasing intensity the “yes” probability starts to increase as well. After a more or less sharp slope, the “yes” probability plateaus and approaches a 100% level.

The detection threshold can be defined wherever the experimenter thinks is most reasonable. Conventionally, the point of 50% detection is reported. The idea is to test a participant repeatedly for different stimulus intensities and then to fit the full psychometric function using a maximum likelihood approach. Once the full curve is estimated, the threshold, i.e. the point of 50% detection, can simply be read off. For a vast majority of redirection studies, this was the preferred method. Specifically for redirection, the estimation is performed by having a user immersed in a VE and asking him/her to walk straight towards a presented virtual target. During the walk, the person is redirected with a curvature gain of a given intensity. After reaching the target the person has to answer whether the applied redirection was felt or not. The procedure is then repeated for a range of curvature gain intensities and the psychometric function and the associated threshold for that person is estimated. This approach is simple and straight-forward to implement; however, there are a couple of dangers linked to it.

The main issue with the yes/no threshold estimation lies in the subjective nature of the posed question. This opens the door for biases to distort the final estimation. People have been shown to exhibit strong “yes” or “no” biases (Gescheider, 1997). This means that for intensities where a person is unsure about whether something was perceived, he/she predominantly gives a negative or positive answer. One person might for example be more comfortable giving a negative answer in uncertain cases and only give a positive answer when he/she is completely certain that a stimulus was presented. In such a case the 50% detection point is shifted towards stronger stimuli. Due to the danger of such biases, using the no/yes approach is usually not recommended. A range of techniques have been developed in the field of psychophysics to deal with the problem. The most simple approach is known as the two-alternative-forced-choice (2AFC) method. In the 2AFC method there is not only one presentation of a stimuli, but always two separated trials. In one trial a stimulus of a certain intensity is presented while in the other trial no stimulus is presented at all. The participant is no longer asked whether he/she has perceived something (yes/no) but challenged to point out in which of the two trials the stimulus was presented (first/second). This question has an objectively correct answer, since there is always one trial with and one trial without stimulus. In the 2AFC setting, subjective biases cannot distort the threshold estimation, since it provides an objective measurement of stimulus detection (Gescheider, 1997). However, as will be discussed at the end of the dissertation, there are still ways in how biases can sneak in, especially in the case of redirected walking. Theoretically though, when applied correctly, the 2AFC method can be considered bias free. The psychometric function alters its shape slightly in the 2AFC setting (see Fig. 2b). Instead of determining the probability of giving a "yes" answer, it now determines the probability of giving the correct answer. For weak stimulus intensities this probability starts at the guessing rate of 50% and increases with stronger intensities. The threshold is conventionally defined as the point of 75% correct detection. Applied to redirection the implementation of the 2AFC method could look the following: A person is asked to walk straight towards a virtual target. This is done two times. In one of the two trials a curvature gain of a certain intensity is applied. After the two trials, the person has to indicate in which of the two walks he/she had been redirected.

One additional complication for measuring redirection thresholds is that redirection can be applied to the left or the right side. Turning the VE to the right, bends the pathway to the right as well, while turning the VE to the left results in a leftward curvature. Thus, it is possible to estimate two separate redirection thresholds for each person, one for left and one for right curves. In the literature of redirection thresholds, this complication has been predominantly handled in the same way. With the intent of having to estimate only one psychometric curve for both the left and the right redirection threshold, researchers have used a slight modification of the yes/no approach. In this approach, the participant is exposed to a curvature gain turning either to the right or the left side. Instead of answering whether anything was felt, the person is asked whether the felt redirection turned to the left or to the right side. The psychometric function, determining the probability of saying "right", starts at 0% for strong leftward redirection and approaches 100% for strong rightward redirection (see Fig. 2c). The 50% point is no longer regarded as a redirection threshold since it describes the point when a person cannot tell whether the redirection went to the left or the right side. Ideally, this should be the point of no redirection at all. The points of 25% and 75% probabilities are reported as the left and rightward redirection thresholds respectively. Somewhat confusingly, in the VR literature the approach is exclusively referred to as a 2AFC method. This is probably due to the two alternative answers that can be given ("left" or "right"). However, labelling this approach as a 2AFC is slightly inappropriate, since it represents rather the characteristics of a yes/no approach. The sole purpose of the 2AFC method is to get rid of subjective biases by having an objective measure of detection. In the left/right approach the yes/no bias is simply replaced by a left/right bias. Thus, some participants, when unsure about the redirection, might rather lean towards guessing a leftward curve instead of a rightward. Similar to the yes/no method this would distort the final estimate of redirection thresholds. How impractical the left/right method is for the case of redirection can be illustrated with a simple thought experiment: It is assumed that a person has a strong rightward bias in his/her answering behaviour. This would entail that the person, when presented with weak redirection, does lean towards guessing the redirection as rightward. As a result, the whole psychometric curve shifts to the left (see Fig. 2d). In an extreme case this could make the rightward redirection threshold, which is the point of giving the answer “right” with 75% chance, “jump” zero and come to lie on the side of leftward redirection (see Fig. 2d). While this might sound far-fetched, in reality it is certainly not and has happened multiple times in our pilot phase, where we experimented with different threshold estimation techniques.

Having a threshold jump zero results in a somewhat nonsensical interpretation of the result. The goal in redirection is to stay within the threshold limits to keep the user ignorant about the manipulation. Thus, in order to not go beyond the rightward redirection threshold, the user would have to be constantly redirected to the left. Not redirecting the user at all would already by out of bounds, because he/she has been shown to detect zero redirection as rightward redirection in more than 75% of cases. Obviously such a conclusion is completely pointless, but it is the direct consequence of trusting the left/right approach.

In addition to the issue of not using a true 2AFC method for threshold estimation, we found another common problem in redirection threshold studies. The issue lies with the use of the constant stimuli method. As briefly mentioned, in the constant stimuli method, the goal is to estimate the full psychometric curve for each participant. In order to be able to fit the full psychometric function, one needs to test a person with many repetitions and at a wide range of stimulus intensities. One possible solution to the problem of many repetitions comes in the form of adaptive threshold estimation methods. Adaptive methods do not estimate the full shape of the psychometric curve, but estimate only one specific point on the curve. Naturally, the detection threshold is the point of interest. To estimate the threshold intensity, much less repetitions are needed because one only needs to test near the true threshold intensity and doesn’t have to cover a wide range of intensities (Watson, 1990).

Since the aim of many redirection studies is to determine only the threshold, it is unnecessary to burden the effort of fitting the full psychometric curve. Adaptive methods achieve a threshold estimation by constantly adapting the tested value based on the previous answers of a participant. If a person for example correctly detects a stimulus at a certain intensity, the intensity can be reduced for the next trial, making the detection more difficult. Conversely, when failing to detect a stimulus, in the next trial a stronger intensity level can be presented, making the detection a bit easier. By adapting the difficulty according to the performance of the participant, the tested intensities oscillate around a specific success probability. There are different methods with which specific points on the psychometric curve can be targeted. The staircase approach is the most simple and most widely used adaptive threshold estimation method (Karmali *et al.*, 2016). To target the 50% point on a psychometric curve a simple 1up-1down staircase can be used. It increases the intensity for negative answers and decreases the intensity for positive answers with the same step size. By changing the step sizes for positive and negative answers one can target other points on the curve as well, such as for example the 75% point (García-Pérez, 2001). The final threshold is estimated as the mean of the tested stimulus intensities.

In our case we decided against the classic staircase approach. The reason was mainly a difficulty in choosing the best step size for the staircase. Choosing too big or too small a step size can have profound effects on how fast and precise a threshold estimation is possible (García-Pérez, 2001). Due to this problem, we ended up using a slightly different adaptive approach, which has been published under the name of QUEST (Watson and Pelli, 1983). QUEST is a Bayesian-based approach to estimating detection thresholds and finds recommendation in the psychophysical literature (Treutwein, 1995). It makes the general assumption that the psychometric function, using a logarithmic stimulus scale, does not change shape between people. Therefore, a more or less sensitive person has the same psychometric function simply shifted to the left or right. This assumption, which is based on a range of psychological experiments, makes the analysis of detection much simpler (Green and Luce, 1975; Nachmias, 1981). QUEST uses a Weibull psychometric function to model a person's answers. In the Weibull function there are two parameters, a position and a shape parameter. The shape parameter, which defines the slope of the psychometric curve has to be set in advance. Fixing the shape parameter leaves only the position parameter to vary freely, which can be set as the threshold intensity of interest (e.g. 75% point). Given this set up, the procedure works in the following way. A person is tested at a specific stimulus intensity and the answer recorded. Based on this answer the current estimate of the detection threshold is calculated using a Bayesian approach. Thus, a prior distribution for the true threshold value, by default a wide Gaussian, is combined with a maximum likelihood fit of the obtained data. The maximum posteriori is the current threshold estimation. For the next trial the posterior distribution becomes the new prior distribution. Using the current most likely estimate of the threshold as the next testing intensity ensures that intensities around the true threshold value are tested, which increases the efficiency of the procedure. The main advantage of QUEST is its straight-forward and fast implementation. In our case it allowed a quick and precise estimation of redirection thresholds using a small set of assumptions. How the realization of our redirection threshold estimation turned out is described in detail in the empirical studies of segment 1: “Redirected walking detection” (see page 29). In conclusion the studies showed that the field of VR research could benefit greatly from psychophysical procedures and that a thorough reflection about the application of these procedures is essential for threshold estimation.

3.1 Investigating the mechanisms of redirection perception

Redirection thresholds are an informative measurement about how sensitive people are to redirection. However, they hardly offer any insight into why some people are more or less sensitive than others. Investigating the origins of the between-participant variance in redirection sensitivity was a central goal of the project. This variance is very striking. While some participants are very sensitive and able to detect curvatures of more than 40 meter radius, other participants can be forced onto a curve of five meter radius without being troubled the least. Finding out why people are better or worse in detecting redirection corresponds to investigating the underlying mechanisms of redirection perception. At the start of the project there was no prior study advancing this inquiry. Given the lack of any prior work, it was clear that the investigation would take on a slightly exploratory character. The general intention was to come up with a series of tasks, which assesses traits relevant for redirection detection. The people who go through this “test battery”, would also have their personal redirection thresholds estimated. To evaluate which traits are truly important for detection, it would subsequently be checked which task performances correlate with redirection thresholds. One simple example of such a trait is balance stability. Balance stability can easily be measured using a balance board. The rational behind the test would be that people who stand more stable are also more sensitive to redirection, because the curved walking shifts the body centre slightly out of balance. On the other hand, people who are more wobbly on their feet would be expected to be more easily fooled by redirection.

The main challenge behind devising the study was to come up with a group of relevant traits, and to find appropriate tests for quantifying these traits. Of all performed experiments in this project, the contribution from the field of psychology was the strongest and most apparent in this study. The process of assembling the tasks, was almost exclusively based on inspiration found in psychological literature and on the expertise of the involved psychologists. However, following the intent of a mutual benefit for both involved fields, the study was not solely fuelled by a curiosity about the psychology of redirection. Having a task, whose performance shows a strong correlation with redirection thresholds, is of potential use to applied redirection as well. The respective task could be used to quickly estimate the personal redirection sensitivity of a user before engaging in a VR experience. The subsequent redirection could then be scaled according to the user's redirection tolerance, making the application more user-adapted.

Given the strong contribution of psychology to this investigation, I would like to illustrate the process of assembling the task-series in more detail. The manipulation of a walking pathway, as it is performed in redirected walking, affects the feedback and interplay of multiple senses. The visual sense is presumably one of the key factors in redirection, since the rotation of the VE is first of all a manipulation of the visual feedback. The subsequent adaptation of locomotion, however, leads to the involvement of more bodily-centred senses. Possible contributions to the detection of redirection could come from proprioceptive, haptic and vestibular inputs. Proprioceptive since the body position is changed in order to walk on a curved pathway. Similarly the haptically felt pressure on the feet could give away the curved walking trajectory. Finally, the vestibular organ could pick up rotations and slight shifts in balance due to the curved walking. Thus, how a person handles the conflicting inputs from the bodily and the visual feedback seems crucial for the detection of redirection. Intuitively, one might come up with the hypothesis, that the better a person can focus on what the body is doing, without being distracted by the visual feedback, the better this person should be able to detect redirection. This assumption formed the basis in our search for appropriate tasks. When looking for helpful concepts in the psychological literature the term “visual dependency” or “visual dominance” repeatedly showed up. The principle of visual dependency states that when being exposed to conflicting feedback from different senses, the visual sense has a tendency to dominate other senses. Published examples include visual dominance over auditive (Witten and Knudsen, 2005), vestibular (Brandt *et al.*, 1998) and proprioceptive perception (Burns *et al.*, 2005).

Interestingly, visual dependency is a measurable, person-specific trait. Thus, there is some variability in how visually dependent people are (Witkin and Asch, 1948). We predicted that people who are more visually dependent, are also more susceptible to redirection, because the visual feedback of a straight walking trajectory more easily dominates conflicting bodily feedback. In redirected walking, however, there are different types of visual dependency that might contribute to redirection sensitivity. For once, people can be visually dependent regarding their vestibular feedback. This could differ from a visual dependency regarding balance control. The goal was to find ways of measuring different facets of visual dependency, which are relevant for redirection. We finally decided on three different visual dependency measurements. The measurements included visual dependency with regard to 1) postural position (rod and frame task), 2) body balance (Romberg quotient) and 3) feeling of self-rotation (vection). This group of tasks stood opposed to a second group of measurements. In the second group we focused on locomotion control and bodily awareness, without considering visual influences. The rational was that a better body-awareness would facilitate the detection of a curved pathway independent of how susceptible a person is to visual interference. The chosen measurements assessed 1) blind locomotion control, 2) balance stability, 3) somatosensory amplification and 4) interoceptive perception.

One point to contemplate about the exploratory approach is the amount of work that the assembly of the task-series involved. Each individual trait of interest and the corresponding ways to assess it, opened up an independent line of research. Thus, an extensive study of literature was necessary to gain an overview of all available methods. In many cases, pinning down the appropriate procedures involved the study of still unresolved discussions in the specific research domains. Only an elaborate consultation of methodological recommendations enabled us to select appropriate tasks. Implementing these tasks required further effort and often demanded the acquisition of additional hardware. Despite the involved effort, the exploratory approach turned out to be an effective way of investigating redirection detection. The procedural details of the chosen tasks and the obtained results are described in the empirical study “Visual capture of gait during redirected walking” (page 32).

4 Relating the feeling of agency to redirected walking

The relevance of redirection thresholds for VR applications is evident. Surprisingly, however, the principle of redirection fits much better into basic psychological research than one might initially think. Distorting the visual feedback of voluntary actions has a long tradition in psychology. Already in 1963, Nielsen used a paradigm, in which the visual feedback of goal-directed hand motions was manipulated. Using a crafty arrangement of mirrors and an intervention of the experimenter, it was possible to insert a lateral drift into the visual feedback of the performed hand movement. The goal was to examine how strong the mismatch between the performed and the perceived action can become, until the manipulation is noticed. The procedure and goal of the Nielsen paradigm strongly reminds oneself of the redirection threshold estimation, although applied to hand movements instead of walking. Over time multiple variations of the Nielsen paradigm were developed to investigate how people process distorted feedback of voluntary actions (Fourneret and Jeannerod, 1998; Fourneret *et al.*, 2001; Farrer *et al.*, 2003). The common theme under which these studies were published, was the term feeling of agency. Feeling of agency describes the sensation of possessing global motor control over a body or object. The goal in the studies was to determine the limits of the feeling of agency for various types of actions. In *2010, Kannape et al.* performed a study, in which for the first time the feeling of agency was investigated for the full body action of walking. Titled "The limits of agency in walking humans", the study made use of a screen, on which participants saw a virtual avatar in front of them. The avatar was mimicking the participants' movements and the task was to steer the avatar into a virtual target using real walking. Similar to the Nielsen paradigm, an artificial drift was inserted into the walking direction of the avatar. Subsequently, participants had to indicate whether they noticed any manipulation, i.e. whether they still felt like having agency over the avatar. Despite small methodological differences (e.g. the use of a display instead of an HMD or the use of a third person perspective), the resemblance between the study and our redirection threshold estimation is astounding. It seems possible that a redirection threshold study could be published exclusively under the banner of feeling of agency in the psychological literature, without ever mentioning the applied aspect of redirection.

The aim of the second segment was to take a more agency-oriented look at redirection in order to bridge the gap between the two lines of inquiry. Thinking about redirection in terms of feeling of agency did open the door to new ideas. One of the main differences between the study of Kannape *et al*. and our redirection threshold estimation was the use of an avatar in the former. The avatar was observed and guided from a third person perspective (3PP). This stands in contrast to classic redirected walking, in which participants observe the VE strictly from a first person perspective (1PP), without seeing a virtual avatar. Given this difference, we intended to extend the study of redirected walking to a 3PP setting. This required the implementation of redirection in 3PP, which did not exist up to this point. In 3PP redirection, users steer an avatar using real walking. Just like in the classic 1PP setting, an induced rotation of the VE forces the user onto a curved walking trajectory. The aim was to examine whether the visual perspective affects redirection sensitivity. In addition to the effect of perspective, we were interested in how feeling of embodiment relates to redirection sensitivity. Feeling of embodiment describes the extent to which a person identifies with a body (or part thereof) and the feeling of agency has been proposed as a sub-component of embodiment (Kilteni, Groten and Slater, 2012). In psychology, embodiment has been extensively studied. Body ownership illusions, such as for example the rubber hand illusion, are used to show how flexible of a process embodiment can be (Kalckert and Ehrsson, 2012). Research about embodiment, however, goes much deeper than body ownership illusions and leads to fundamental questions about the basis of a sense of self (Blanke and Metzinger, 2009). In the VR literature, embodiment is rather looked at from an application-oriented perspective. When using an avatar in a VR application, eliciting a feeling of embodiment is vital to achieve a strong sense of immersion.

To get a closer look at the effect of embodiment on redirection sensitivity, we intended to artificially decrease the feeling of embodiment in participants. One regularly used technique to decrease the feeling of embodiment is to distort the synchrony of body movements between a user and his/her virtual body (Kalckert & Ehrsson, 2012; Liang, Chang, Chen, Huang, & Lee, 2015). Thus, participants would still be able to steer the avatar, but the walking motion, like swinging the arms and legs for example, would not agree with the real movements. The aim was to see how redirection thresholds are affected by such an intervention. While the influence of perspective and embodiment on redirection sensitivity are of general interest for psychological research, it is also of use for VR research. Although 1PP is so far the dominantly used perspective in VR, there are increasing attempts to apply a 3PP as well. One possible advantage of 3PP is that it might reduce the susceptibility to motion sickness, which is still a large problem in VR (Monteiro *et al.*, 2018). With future 3PP applications in mind, the investigation of redirected walking in 3PP becomes vital. A difference in redirection sensitivity between the two perspectives would have profound implications. Knowing how the quality of an avatar, i.e. the synchrony between the avatar's and the participant's movements, is affecting redirection can be of equal importance.

How we specifically implemented the 3PP redirection and how embodiment affected redirection thresholds, is described in the empirical study "The role of perspective and embodiment in redirected walking" (page 73).

5 Predicting future pathways in virtual environments

So far, the described research exclusively dealt with the perception of redirection. However, in the third segment of this project we focused on a completely different issue. The aim was to investigate how well future walking pathways of VR users can be predicted. On first sight, this investigation seems to be completely unrelated to the theme of redirected walking. Understanding why pathway prediction is important for applied redirection, and how the psychological sciences got involved in the endeavour, needs a bit of explanation. As previously described, modern redirection systems operate in an adaptive fashion. Depending on the position of the user in the physical room, the most appropriate redirection measures are chosen and applied. For example, a user walking with a wall to his/her right, could be guided away from the wall with a leftward curvature gain. A next step to increase efficiency is to incorporate the position of the user inside the virtual world. If in the above example the person is inside a virtual corridor, which anyway is about to make a left turn, no redirection would have to be applied. Thus, by incorporating the structure of the physical and the virtual environment, the most ideal redirection can be chosen. A further step to improve efficiency, is to make probabilistic predictions of a user's future walking pathway. In the example with the corridor there is only one way for the user to go, so the prediction is redundant. Often, however, users can choose different directions like for example in open spaces or when encountering junctions. The chosen direction in an upcoming junction can have a significant impact on the choice of the appropriate redirection method. Thus, knowing about inherent walking patterns of users could help improve redirection.

5.1 Spontaneous alternation behaviour

The hope on the VR side of the collaboration was that the psychological sciences had something to offer regarding the prediction of walking pathways. The answer came in the form of spontaneous alternation behaviour (SAB). Simply put, SAB describes the tendency to alternate successive direction choices when exploring a corridor-based maze. SAB was originally discovered in rats in 1925 (Tolman, 1925; Dember and Richman, 1989). When exposed to a T-maze twice, it could be shown that in the second exposure rats preferred the previously not visited goal arm. This inherent drive to alternate direction choices was subsequently studied and demonstrated in a wide range of animal species (Richman, Dember and Kim, 1986). Using SAB to predict walking pathways in VR is straight forward: If a person takes a turn in a certain direction, he/she is more likely to turn in the opposite direction in a subsequent junction.

Using SAB as the principle of choice, did not happen by mere coincidence. Prof. Brugger has spent large parts of his research career with the study of random number generation in humans. Random number generation poses the task of generating a number sequence, which is supposed to be as random as possible. One specific form of a random number generation task is the Mental Dice Task (MDT). In the MDT new numbers ranging from one to six have to be generated with a 1Hz frequency. The number sequences of humans reveal a common pattern. When trying to be random, humans tend to switch numbers too often, i.e. there are not as many number repetitions as a real dice would produce. This robust finding is generally referred to as repetition avoidance (Geisseler *et al.*, 2016). Since SAB also represents an avoidance of repeating the same answer (i.e. the turning direction), the conclusion presents itself that SAB in animals and repetition avoidance in humans are based on a common, fundamental process. Thus, for Prof. Brugger it was a somewhat lucky and unforeseen development that a collaboration with a VR lab would offer a chance to perform a human SAB study. Although SAB was demonstrated in a variety of species, SAB in humans had only been investigated superficially. One of the main reasons for the lack of human SAB studies is the difficulty of building life-size mazes for human walkers. As a surrogate, human alternation behaviour had mainly been examined using stylus mazes on paper. In contrast to the effort of building a real physical maze, virtual mazes can easily be generated in whatever shape needed. The visual appearance of the maze and its surroundings can be perfectly controlled for in VR. With the help of position tracking users can walk through the virtual mazes. Coincidentally, VR seems to offer an ideal set up to investigate human SAB. Again, the by now familiar pattern of a simultaneous profit for both collaborating parties emerged.

How the investigation of human SAB was realized and whether humans do indeed exhibit SAB when walking through virtual mazes is described in the empirical studies of segment 3: “Spontaneous alternation behaviour in VR” (see page 30).

PART II

EMPIRICAL STUDIES

6 Empirical studies overview

6.1 Segment 1: Redirected walking detection

The aim of the first segment was to determine the redirection thresholds of healthy adult participants and to determine the psychophysical traits relevant for redirection detection. Additionally we tested the effects of a variety of external factors on redirection thresholds.

The key findings of the segment included:

- Participants' mean redirection threshold was estimated at a curvature with 9.5 meter radius.
- A significant gender effect was found with men being more sensitive to redirection than women.
- Visual dependency assessed with the rod and frame test showed a significant negative relation with redirection sensitivity.
- A significant walking speed effect was found with faster walking speed facilitating redirection detection.
- No effect on redirection thresholds due to a difference in the VE size was found (corridor vs. room).

In total, the segment consisted of one large study, which resulted in the publication of one journal paper and two conference papers:

1. **Rothacher**, **Y**., Nguyen, A., Lenggenhager, B., Kunz, A., Brugger, P., (2018). Visual capture of gait during redirected walking. *Scientific Reports*, 8(1), 17974. doi: 10.1038/s41598-018-36035-6

2. Nguyen, A., **Rothacher**, **Y**., Lenggenhager, B., Brugger, P., Kunz, A., (2018). Individual differences and impact of gender on curvature redirection thresholds. *Proceedings of the 15th ACM Symposium on Applied Perception - SAP '18*, 1-4, doi: 10.1145/3225153.3225155

3. Nguyen, A., **Rothacher**, **Y**., Lenggenhager, B., Brugger, P., Kunz, A., (2018). Effect of environment size on curvature redirected walking thresholds. *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 645-646, doi: 10.1109/VR.2018.8446225

6.2 Segment 2: Visual perspective and feeling of embodiment in redirected walking

The aim of the second segment was to investigate how redirection sensitivity compared between a first person and a third person perspective setting. In addition, the aim was to examine how an altered sense of embodiment over a virtual avatar affected redirection sensitivity.

The key findings of the segment included:

- No significant difference in redirection thresholds between the 1PP and the 3PP condition was found.
- Altering the synchrony between the avatar's and the participants' movements did not show a significant effect on redirection thresholds.
- Redirection sensitivity correlated positively with experienced feeling of agency

In total, the segment consisted of one study, which resulted in the generation of one manuscript:

1. **Rothacher**, **Y**., Nguyen, A., Lenggenhager, B., Brugger, P., Kunz, A.,
The role of perspective and embodiment in redirected walking.
Awaits submission.

6.3 Segment 3: Spontaneous alternation behaviour in VR

The aim of the third segment was to investigate whether adult human walkers exhibit SAB when exploring virtual mazes. In addition, we aimed at examining the underlying mechanisms and the generalizability of human SAB. Finally, the relation between SAB and the avoidance of repetitions in random number generation was assessed.

The key findings of the segment included:

- Adult walkers showed a general tendency to alternate directions with a significant rate of approximately 60%.
- Alternation rates were not significantly affected by increased cognitive load.
- No distinct effects of the visual and the physical component of a forced turn on alternation rates were found.
- No significant alternation of turn direction was found in an open, unrestricted space.
- No significant relation between random number generation and SAB was found.

In total, the segment consisted of two studies, which resulted in the publication of one conference paper and the submission of one journal paper:

1. Nguyen, A., **Rothacher**, **Y**., Lenggenhager, B., Kunz, A., Brugger, P., (2017). Spontaneous Alternation Behaviour in Humans. *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*, 1-4, doi: 10.1145/3139131.3139168

2. **Rothacher**, **Y**., Nguyen, A., Lenggenhager, B., Kunz, A., Brugger, P. Walking through virtual mazes: Spontaneous alternation behaviour in human adults.
Registered report submitted to *Cortex*.
Accepted stage 1 protocol: April 2019.
Submission of stage 2 protocol: September 2019

7 Segment 1, study 1: **Visual capture of gait during redirected walking**

Abstract

Redirected walking allows users of virtual reality applications to explore virtual environments larger than the available physical space. This is achieved by manipulating users' walking trajectories through visual rotation of the virtual surroundings, without users noticing this manipulation. Apart from its applied relevance, redirected walking is an attractive paradigm to investigate human perception and locomotion. An important yet unsolved question concerns individual differences in the ability to detect redirection. Addressing this question, we administered several perceptual-cognitive tasks to healthy participants, whose thresholds of detecting redirection in a virtual environment were also determined. We report relations between individual thresholds and measures of multisensory weighting (visually-assisted postural stability (Romberg quotient), subjective visual vertical (rod-and-frame test) and illusory self-motion (vection)). The performance in the rod-and-frame test, a classical measure of visual dependency regarding postural information, showed the strongest relation to redirection detection thresholds: The higher the visual dependency, the higher the detection threshold. This supports the interpretation of users' neglect of redirection manipulations as a "visual capture of gait". We discuss how future interdisciplinary studies, merging the fields of virtual reality and psychology, may help improving virtual reality applications and simultaneously deepen our understanding of how humans process multisensory conflicts during locomotion.

7.1 Introduction

Virtual reality (VR) applications using head mounted displays (HMDs) allow users to deeply immerse in a virtual environment (VE). There is, however, one obstacle to a full-blown immersion, dubbed the "locomotion problem". It concerns the user's navigation through large VEs. While virtual worlds can easily be expanded infinitely, physical locomotion remains constrained by the dimensions of the available room. Early attempts to overcome this locomotion problem made use of keyboards and joysticks thus engaging the hands for a task meant, in reality, for the legs. This crude simulation of locomotion was quickly followed by more sophisticated solutions using treadmill-like devices that allow users to physically walk on the spot in order to move through virtual space (Medina, Fruland, (Medina, Fruland and Weghorst, 2008; Souman *et al.*, 2011). While such solutions made it possible to “walk” infinitely far in a VE, they are still a cumbersome approximation to real walking. Position tracking technology offers the possibility to translate real walking movements into virtual movements (Ward *et al.*, 1992). While this approach produces the exact sensation of real walking, a new problem arises. Due to the HMD, the user is blind to real world obstacles like walls and other objects in the physical room. Because VEs are often larger in size than the available physical space, collisions with physical boundaries become an issue.

Redirection or redirected walking is a software-based approach to addressing this problem (Razzaque, Kohn and Whitton, 2001). By controlling how real-life movements are mapped onto virtual space, redirection aims at manipulating a user’s physical walking trajectory. The focus of the present study is on one key technique of redirection, the so-called “curvature gain” (Neth *et al.*, 2012). Applying a curvature gain induces a rotation of the virtual scenery around a user while (s)he is moving. This causes the user to correct for the rotation by walking on a curved pathway (Fig. 3). At the extreme, a user could proceed infinitely far straight forward in the VE while walking in a full circle in reality. Modern algorithms dynamically apply curvature gains based on a user’s position in the virtual and physical environment with the goal to steer the user away from walls, thus making it possible to explore virtual areas much larger than the available physical space (Zmuda *et al.*, 2013; Hodgson, Bachmann and Thrash, 2014; Nescher, Huang and Kunz, 2014). The magnitude of a curvature gain is defined as the inverse of the curvature radius.

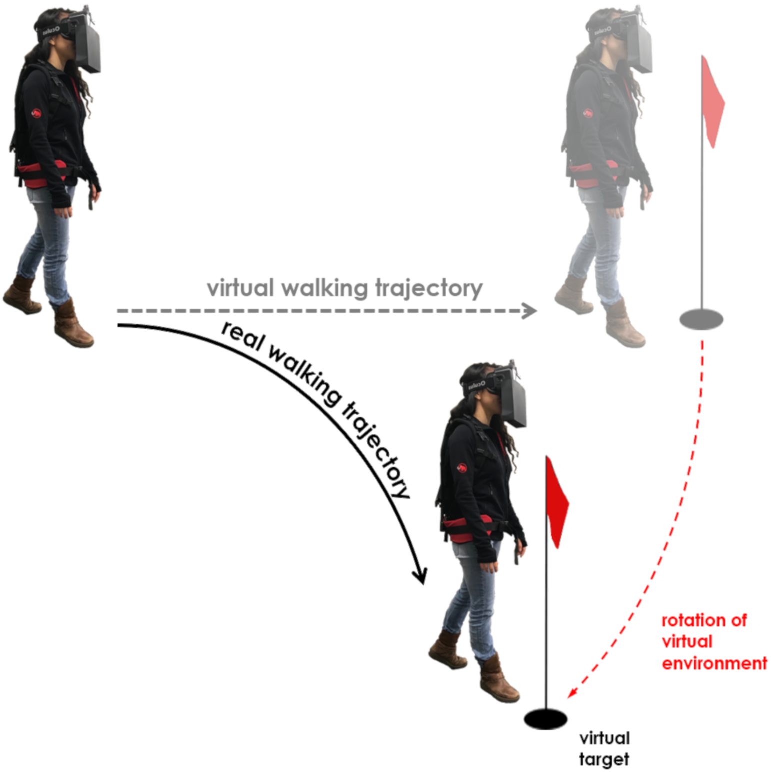


Fig. 3: Illustration of a walking trajectory manipulation through redirected walking using a curvature gain.

As long as the radius of a forced curvature is not too small, users fail to notice the manipulation and assume that the virtual walking trajectory corresponds to the real one. Several studies exist that measured the perceptual limits for curvature gains to remain unnoticed. Knowing users' redirection thresholds is crucial for an immersive virtual reality experience since full immersion will only be guaranteed as long as there is a felt harmony between what one's eyes see and what one's legs do. Somewhat surprisingly, the radii of threshold-curvatures vary considerably across several studies, ranging from 5m to 22m (Steinicke *et al.*, 2010; Grechkin *et al.*, 2016). The variability in these redirection thresholds is possibly due to differences in the applied threshold estimation methods, differences in the architecture and design of the used VEs or more general differences such as dissimilar study populations.

Apart from its value for designing VR-applications, we argue that the issue of redirection is also of considerable interest for psychological research. During walking, redirection causes a mismatch between visual and bodily feedback, the latter comprising vestibular, proprioceptive and somatosensory cues. Experimentally induced sensory mismatch situations have long been used in psychology to study a broad range of phenomena, from motion sickness (Warwick-Evans *et al.*, 1998), multisensory integration (Bertin and Berthoz, 2004; Grace Gaerlan *et al.*, 2012) and the development of a “bodily self” (Macauda *et al.*, 2015) to action monitoring (Bock, 1992; Fourneret and Jeannerod, 1998) and the feeling of agency (Farrer *et al.*, 2003; Leube *et al.*, 2003; Kannape *et al.*, 2010; David *et al.*, 2011; Kang *et al.*, 2015).

More than half a century ago, Nielsen introduced a paradigm which allowed the manipulation of the visual feedback of a performed hand action, specifically drawing of a straight line in the sagittal direction (Nielsen, 1963). With the aid of a mirror, a participant would either see his or her real hand while drawing, or the reflection of the experimenter’s hand in its place. In trials where the experimenter’s hand was visible, the experimenter followed the trajectory of the line produced by the participant but induced a slight lateral deviation. Tricked into believing the experimenter’s hand was theirs, participants, unbeknownst to them, deviated to the opposite side in an attempt to correct for the covert redirection. Nielsen’s paradigm, conceptually reminiscent of redirected walking, proved most influential; it induced a large number of authors to apply modifications of the procedure in the investigation of various aspects of action monitoring and self-recognition. In a seminal study on agency, a sensorimotor adjustment task was applied, in which the visual feedback from goal-directed hand movements was manipulated using angular deviations (Fourneret and Jeannerod, 1998). This procedure was used to study the conscious monitoring of action in healthy participants. It became again evident that participants automatically adjusted their hand trajectory in order to correct for the induced deviation. Despite this correction, participants ignored the veridical trajectory of their hand when consciously judging its travelled direction. This suggests that participants dominantly relied on visual cues when attributing the observed action, ignoring contradicting proprioceptive signals. Follow-up experiments laid the focus on the cues responsible for the conscious experience of agency. In one exemplary study, participants observed a screen showing either their own hand or the experimenter's hand (Daprati *et al.*, 1997). They were required to perform a simple hand motion in response to an acoustic signal while monitoring the visual feedback on the screen. The experimenter would simultaneously perform the same or a different hand motion. Subsequently, participants had to judge whether the observed hand had been their own or the experimenter's. It could be shown that in the condition where the experimenter performed the same hand movement, the subjects’ performance deteriorated, they mistook the experimenter’s hand as their own in about 30% of trials. It was concluded that subjects based their judgement on slight differences in timing and kinematics, but often these differences were not sufficient to discriminate own and foreign hand actions. These types of paradigms were also applied to clinical populations, classically individuals diagnosed with schizophrenia. Schizophrenic individuals show a disturbance in the attribution of actions, often assigning their own actions and thoughts to alien sources or conversely conceive themselves as the agent of actions performed by others (Schneider, 1959; Frith, 1987). When exposed to the type of experimental situations described above, schizophrenic individuals showed a systematic tendency to attribute the experimenter's actions to themselves (Daprati *et al.*, 1997; Fourneret *et al.*, 2001).

While initially only motor actions involving the hands were investigated, recent studies have transferred the concept of an induced mismatch between a performed action and it’s visual feedback to the full body action of walking (Kannape *et al.*, 2010, 2014). The participants, who were placed in a tracking area, observed a virtual room projected on a large screen in front of them. An avatar in the virtual room was continuously mimicking the participants’ body-movements. Participants were then required to steer their “virtual body” into a virtual target using real walking. By inducing a lateral drift in the movements of the avatar and testing the participants’ sensitivity to that manipulation, the limits of the feeling of agency for human walking were determined (Kannape *et al.*, 2010). This walking paradigm was recently used in a clinical context and allowed the demonstration that awake sleepwalkers differ from healthy participants in the conscious monitoring of gait (Kannape *et al.*, 2017).

At this point it becomes evident that although redirected walking has been developed without any intent to apply it in psychological research, the paradigm seems to perfectly line up with the advancement of agency and action recognition studies so far. The above-described setup for studying the feeling of agency in human walking resembles the classical situation of redirection to a remarkable degree. However, some major differences between the two methodologies have to be noted. First, in redirected walking an HMD instead of a projection screen is used, which allows a larger walkable tracking area to be used and avoids any irritation stemming from a mismatch between real and virtual visual cues. Second, redirection is usually applied in a first-person perspective scenario, therefore implementation of a virtual avatar is feasible, but not necessary. This use of a first-person perspective might bring the benefit of a more natural immersion during an experimental procedure. Lastly, the applied manipulations of the walking trajectory differ slightly between the two setups. Common redirection paradigms use a rotation of the VE to influence walking users while traditional work on agency detection have rather introduced a lateral (angular) drift.

Classically, the aim of agency studies based on some modification of the Nielsen paradigm (Nielsen, 1963) is to explore the extent to which participants can be disrupted in their feeling of agency. Often this is accompanied by the estimation of a feeling of agency threshold. In the case of redirection, there has also been some effort dedicated to estimating users' detection thresholds under various conditions (Steinicke *et al.*, 2010; Neth *et al.*, 2012; Grechkin *et al.*, 2016; Langbehn *et al.*, 2017). However, the neuropsychological factors determining this threshold have, to the best of our knowledge, never been systematically investigated.

In order to address this gap in knowledge, the present study set out to determine the perceptual and cognitive factors contributing to a person's ability to detect redirection of gait in a VE. As described above, redirection causes a sensory mismatch between the visual and bodily feedback during walking. Previous studies on action recognition and basic research in multisensory processing would suggest that visual dominance over the other senses is responsible for the incomplete awareness of being redirected along a visually guided path. In situations of multisensory conflicts, human observers tend to believe their eyes rather than their ears (Witten and Knudsen, 2005), their proprioceptive sense (Burns *et al.*, 2005), or their vestibular perception (Brandt *et al.*, 1998). This dominance effect is generally interpreted as a "visual capture" of non-visual senses. Alternatively (or in addition), studies investigating locomotor control in blindfolded walkers have proposed a general insensitivity to noise in the motor output, and thus a lack of non-visual body awareness, as a key factor limiting healthy subjects' sensitivity to detect curved walking trajectories (Kallie, Schrater and Legge, 2007; Souman *et al.*, 2009).

To test whether similar mechanisms are responsible for the perception of redirected walking, we assessed healthy participants' curvature gain detection thresholds in a well-defined redirection paradigm and had each participant perform a series of carefully selected tasks. In total, six different tasks were employed with the goal to capture the full range of psycho-physical traits suspected to be of importance for the detection of redirection (see Table 1). The six applied tasks were divided into two groups, where the first group addressed visual dependency measures (i.e. the degree of reliance on visual cues relative to cues of other modalities; Table 1, top), while the second group assessed non-visual body control and awareness (Table 1, bottom).

Given the wide variety of cues and modalities, in relation to which visual dependency can be examined, the first three tasks were selected with the intent to measure visual dependency specifically regarding gait-relevant sensory cues. As a result, the three visual dependency measures included 1) visual dependency in relation to postural information using a rod-and-frame test, 2) visual dependency in relation to experience of self-motion using a vection susceptibility test, and 3) visual dependency in relation to postural control using a Romberg test.

The rod-and-frame test, originally developed by Witkin and Asch in the late 1940s (Witkin and Asch, 1948), requires a subject to align a rod inside a slanted frame until it is perceived as vertical. Originally devised to assess human subjects' "sense of space" (Witkin and Asch, 1948), the rod-and-frame test has advanced to a standard procedure to study interactions between the visual, vestibular and proprioceptive senses (Corbett and Enns, 2006). Today the test is commonly used as a visual dependency measurement and assesses the degree, to which a person relies on visual rather than postural information to judge the gravitational vertical. Interestingly, and perhaps even more relevant for the case of redirection, the performance in the rod-and-frame test has also been linked to body-awareness, showing that subjects with lower rod-and-frame test performance ("field-dependent") are more susceptible to the rubber hand illusion (David, Fiori and Aglioti, 2014). In order to perform well in the rod-and-frame test, the tested person has to focus on vestibular and proprioceptive cues while ignoring the visual experience of the slanted frame. We hypothesized that during redirection, participants also must focus on postural information while ignoring contradicting visual cues to detect the curved walking trajectory. Thus, we expected participants, who perform better at the rod-and-frame test, to be less easily tricked by redirected walking.

Vection designates the illusory perception of own-body movement during the visual observation of moving objects in the environment and is commonly used as a test of visual dependency in visual-vestibular conflicts (Dichgans and Brandt, 1978; Kim *et al.*, 2015). Vection is the powerful sensation known by everybody who has ever looked out through the window of a stationary train, thinking that it is moving just before noticing that in fact it is the train on the opposite track that has started to move. Specifically, circular vection refers to the illusion of self-rotation on observing vertical stripes on a surrounding surface (traditionally an “optokinetic drum”) that moves around the upright axis of the body. Similar to circular vection, redirected walking exposes participants to a visual-vestibular conflict due to the visual rotation of the VE around the moving participant. We hypothesized that participants, who are more visually dominated in visual-vestibular conflicts and thus more susceptible to vection, would also have more difficulties detecting the visual-vestibular mismatch elicited by the rotating VE during redirected walking.

The Romberg test is a standard tool used in sway analysis and aims at identifying the influence of vision on postural control (Lê and Kapoula, 2008). The amount of body sway occurring when attempting to stand still reflects a person’s postural stability. Therefore, visual dependency in relation to postural control can be measured by how much the body sways when the eyes are opened compared to when the eyes are closed. The ratio of the sway path lengths under these two conditions is referred to as the Romberg quotient. Similar to the rationale behind the rod-and-frame test and the vection susceptibility test we hypothesized that participants who are less visual dependent in their postural control would have less difficulties detecting disruptions in their postural balance due to the curved walking trajectory, despite contradicting visual inputs.

In addition to these three tasks assessing different facets of visual dependency, three further tasks were chosen to assess non-visual body control and awareness. These tasks aimed at measuring 1) participants’ non-visual locomotor control using a blind veering test, 2) participants’ sensitivity to interoceptive cues using a heartbeat detection task, and 3) participants’ sensitivity to somatosensory inputs using the somatosensory amplification (SSA) scale.

Blind veering refers to any lateral deviation when trying to walk a straight line without any visual feedback (Kallie, Schrater and Legge, 2007). With the visual feedback completely removed, the blind veering test assesses a person’s ability to identify a straight walking direction using only non-visual cues. Therefore, the performance in a blind veering test is a measure of a person’s bodily awareness. Since the detection of redirected walking requires participants to identify non-straight walking trajectories, we hypothesized that a heightened awareness of non-visual locomotor-related cues, as measured by the veering test, would serve as an advantage in detecting redirection.

In contrast to the highly locomotion specific form of body awareness assessed by the blind veering test, a more generic type of body awareness can be measured using interoception tests. Interoception describes the perception of the internal state of the body and its visceral organs (Garfinkel *et al.*, 2015). The importance of interoception for navigating in VEs has recently been emphasized (Tcheang, Bulthoff and Burgess, 2011). Also, a high interoceptive sensitivity has previously been linked to a lowered propensity for experiencing a bodily illusion resting on multisensory conflict (Tsakiris, Jimenez and Costantini, 2011). Classically, interoception is measured in cardiac-based tasks. The heartbeat detection task requires a person to identify whether a series of acoustic signals is synchronous or out-of-sync with his/her heartbeat (Kleckner *et al.*, 2015). A person, who performs well in this test, could be assumed to be more aware of their internal cues, potentially being less distracted by concurrent visual cues. We thus hypothesized that a generic bodily awareness, expressed by a person's interoceptive sensitivity, would facilitate the detection of the body's curved walking trajectory during redirection.

Finally, the SSA scale questionnaire can be used to assess a heightened attention to uncomfortable bodily sensations (Barsky, Wyshak and Klerman, 1990). We hypothesized that such a heightened attention could be beneficial in detecting potential, uncomfortable bodily sensations triggered by redirection.

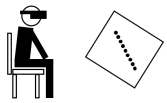
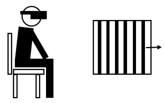
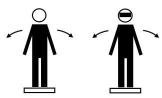
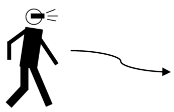
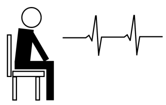
	Task	Assessed Variable(s)	Reference	
Visual-dependency measures	**Subjective visual vertical (rod-and-frame test)**: Participants view a virtual rod surrounded by a tilted frame presented on an HMD. The task is to rotate the rod until it is aligned in a perfectly vertical orientation.	*Rod-and-frame mean angle:* Mean angular deviation of the subjective visual vertical from the true vertical	Takasaki et al. 2012	
	Illusory self-motion (vection): Participants observe a white surface with black vertical stripes (on an HMD). The stripes start moving in one lateral direction and participants (1) indicate the onset of self-motion and (2) rate the intensity of that sensation (on a 100-point scale).	*Vection mean onset time:* Mean duration until a participant indicates a sensation of motion *Vection mean strength:* Mean rated intensity of self-motion	Kim et al. 2015	
	Visually-assisted postural stability (Romberg quotient): Participants stand on a balance board measuring centre of pressure (COP) coordinates. Standing must be as motionless as possible for two minutes. There are two trials, one with eyes open and one with eyes closed.	*Romberg quotient:* The total sway path length with eyes-closed divided by the total sway path length with eyes-open	Lê & Kapoula 2007	
Blind locomotion control and interoceptive awareness	**Blind veering**: Participants repeatedly walk a given distance blindfolded with the task to walk as straight as possible.	*Blind-walking mean angle:* Mean lateral deviation from straight-ahead per step *Blind-walking angle sd:* Sample standard deviation of the lateral deviations per step	Kallie et al. 2007	
	Interoception (heartbeat detection task*):* Participants repeatedly hear series of beep-sounds synchronous or asynchronous with their own heartbeat and must identify (a)synchrony of the playbacks.	*Interoceptive sensitivity:* percentage of correct answers in the heartbeat detection task	Kleckner et al. 2015	
	Somatosensory amplification (SSA)*:* Participants complete a 10-item questionnaire assessing an increased attention to uncomfortable bodily sensations.	*SSA score:* Total score in the SSA questionnaire	Barsky et al. 1990	

Table 1: Short descriptions of the applied tasks and the thereof derived variables. For more details see text.

7.2 Methods

7.2.1 Participants

Sixty people, 30 women and 30 men, aged between 18-35 years (mean age: 25.1 years, SD: 3.9 years) participated in the study. Their average duration of education was 16.1 years (SD: 3.8 years) and on average they spent 1.8 hours a week video gaming (SD: 3.9 hours) and 3.4 hours a week exercising (SD: 3.2 hours). Exclusion criteria included any history of neurological or vestibular disease and any type of injury affecting natural walking. Participants were right-handed according to a validated lateral preference inventory (Coren, 1993). They were mostly recruited through the online market-place of the University of Zurich. The participants signed an informed consent sheet prior to starting the experiment. All experimental procedures were approved by the Cantonal Ethics Committee of Zurich (BASEC Number: 2016-01153) and carried out in accordance with the ethical standards of the Declaration of Helsinki.

7.2.2 Redirection procedure and threshold assessment in a VE

Participants wore an Oculus DK2 HMD and were connected to an Intersense IS-1200 optical tracking system for 6 DOF head position tracking at 180Hz (Foxlin and Naimark, 2003). They started at one end of a 12m x 6m tracking area and found themselves in an empty virtual room with a floating red sphere 7.5m in front of them (Fig. 4). Redirection thresholds were determined in a two-alternative forced choice task (2AFC task). Participants were asked to walk straight to the virtual target (floating red sphere) for two consecutive trials. Just in one of these two trials, a curvature gain of a predefined intensity was applied. The task for the participants consisted of identifying, immediately after the completed two trials, in which trial the redirection had taken place. An eye-tracker integrated in the HMD allowed the participants to give their answer by looking at corresponding icons ("first trial" vs. "second trial") shown on the display. Depending on whether the answer was correct or not, the intensity of the curvature gain was automatically adapted for the next round in order to make the task more or less difficult. Whether redirection was applied in the first or second trial was randomly distributed. We used the Bayesian-based adaptive method QUEST to choose appropriate stimulus levels for each round and to estimate the final threshold value

(Watson and Pelli, 1983). The performance in such a 2AFC task is modelled as a psychometric curve, in which the probability of a correct answer is plotted against the applied stimulus intensity (in our case curvature gain magnitude). The psychometric curve theoretically starts at a guessing rate of 50% for low stimulus levels and approaches a 100% detection rate with increasing stimulus intensity. The detection threshold on this curve is classically defined as the stimulus level with a 75% detection rate. We used separate, interleaved QUESTs for each participant in order to estimate independent detection thresholds for left- and rightward redirection. In total, each participant completed 160 rounds, each consisting of two trials, respectively. Walking speed was controlled by a metronome, to which the participants were asked to adjust their step frequency. The frequency of the metronome was adapted to each participant based on the formula by Dean, 1965 (Dean, 1965), targeting an average walking speed of 1m/s. Before starting the threshold assessment procedure, participants completed a set of practice rounds to make sure that the task was understood, and that the adaptation of the walking speed and the use of the eye-tracker were sufficiently mastered. A custom-made cover in front of the HMD ensured that participants could not get any visual cues from their surroundings.

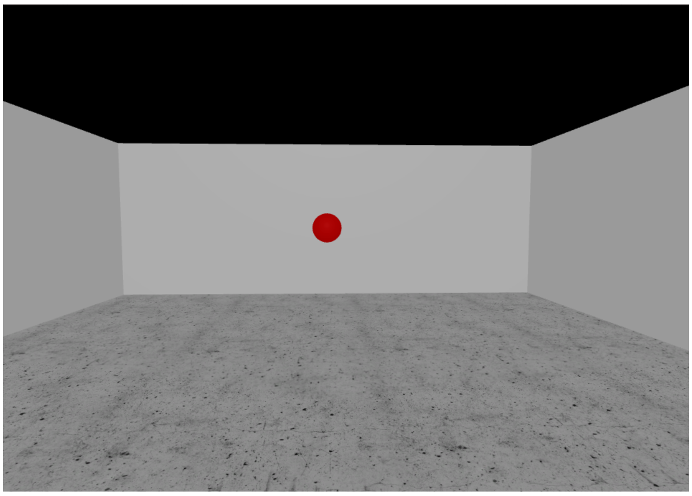


Fig. 4: Screen-shot of the virtual environment used in the redirection threshold assessment. The red sphere, serving as the participants' target, is visible in the middle.

7.2.3 Perceptual and cognitive tasks

Table 1 provides an overview of the tasks and variables used to determine the factors related to participants' redirection thresholds. In total, participants completed the following six tasks: (1) A rod-and-frame test, which is the classical measurement of visual dependency regarding vestibular and proprioceptive signals; (2) a vection susceptibility test, which is an assessment of visual dependency during judgements of illusory self-motion; (3) a Romberg test, which determines the visual dependency in postural stability; (4) a blind veering task, which quantifies non-visual, locomotion-related body control; (5) a heartbeat detection task, which scores the participant's interoceptive abilities; and (6) a somatosensory amplification questionnaire, which assesses an increased attention to uncomfortable bodily sensations.

The procedures of the single tasks are introduced here in more detail and grouped according to whether they involve the visual sense or rather emphasize non-visual, locomotion-related processing or interoceptive awareness.

7.2.3.1 Tasks mainly involving vision

Subjective visual vertical (rod-and-frame test)

For our study we deployed a VR-adapted version of the rod-and-frame test (Bagust, Rix and Hurst, 2005). Participants wore an Oculus DK2 HMD while sitting upright on a chair. On the HMD, they were presented a virtual, tilted frame surrounding a rod that could be rotated using a joystick. They were required to set the rod in a perfectly vertical orientation. The virtual rod was composed of a dotted line to prevent giving any cues about its orientation due to the limited resolution of the HMD (Docherty and Bagust, 2010). Each participant completed 20 trials consisting of a randomized, balanced set of a frame tilted ±20° paired with a rod, initially tilted ±18° (Takasaki *et al.*, 2012).

Based on the 20 trials, the rod-and-frame mean angle was calculated for each participant. This is the average of the 20 (unsigned) angular deviations of the subjective visual vertical from the true vertical.

Illusory self-motion (Vection)

For the vection susceptibility test, participants were seated upright on a stationary chair and observed a pattern of vertical black and white stripes on an Oculus DK2 HMD. Upon button press, the virtual drum started rotating, increasing rotation speed for 6 seconds (acceleration:

10 degree/s^2) and ending up at a constant speed of 60 degree/s (Melcher and Henn, 1981). Participants had to focus on the moving surface and report by button press as soon as they felt the sensation of themselves rotating instead of merely looking at a rotating surface. If no such sensation occurred, the simulation would stop after 30 seconds. Following each trial, participants had to rate the strength of the movement sensation on a scale of 0-100, with 0 denoting no sensation of movement, and 100 denoting a sensation indistinguishable from real movement. In total, participants completed eight trials, consisting of four leftward and four rightward rotations presented in a randomized order.

Based on these eight trials, the vection mean onset time, which is the average duration until a participant presses the button indicating a sensation of movement and the vection mean strength, which is a participant's average rating of the strength of his/her sensations of movement, were calculated for each participant.

Visually-assisted postural stability (Romberg quotient)

The amount of body sway occurring when attempting to stand still reflects a person's ability of postural control. Using a Wii balance board (Clark *et al.*, 2010), each participant was instructed to stand as still as possible without shoes in a natural, shoulder wide stance, arms hanging down on the side under two conditions. In the first condition, participants kept their eyes open while fixating a cross at eye level 40cm in front of them. In the second condition, participants kept their eyes closed. Each condition lasted two minutes. During both conditions, the coordinates of the participants' centre of pressure (COP) were recorded.

Using the recorded COP coordinates, the total sway path length was calculated for the eyes-open and eyes-closed condition. In order to quantify the influence of vision on sway, the Romberg quotient was calculated for each participant. This is the common measure of visual dependency in sway analysis (Lê and Kapoula, 2008). The Romberg quotient is derived by dividing the total sway path length with eyes closed by the total sway path length with eyes open.

7.2.3.2 Tasks focusing on non-visual senses

Blind veering

To quantify a person's blind veering tendency, we adapted the procedure described by Kallie *et al.* (2007). The same VR set up used for the redirection threshold estimation was employed. Participants wore an Oculus DK2 HMD and were connected to an Intersense IS-1200 optical tracking system for 6 DOF head position tracking at 180Hz (Foxlin and Naimark, 2003). The participants started at one end of the 12m x 6m tracking space and were exposed to a completely dark VE except for a floating red sphere 9.5m in front of them. Participants were instructed to walk straight towards this sphere. After a walked distance of 1m, the red sphere disappeared, leaving the moving participants effectively blindfolded. Participants were beforehand instructed to keep on walking as straight as possible, as if the target would still be visible. In each trial participants were required to walk until they crossed the frontoparallel plane located 8m from the starting position, at which point an instruction to stop appeared on the HMD. In total, each participant completed 40 trials. A cover in front of the HMD ensured that participants could not get any visual cues from their surroundings. Walking speed was controlled by a metronome, to which the participants were asked to adjust their step frequency. The frequency of the metronome was adapted to each participant based on the formula by Dean, 1965, targeting an average walking speed of 0.75m/s. Based on the head tracking data, the walking trajectories of the participants were generated and separated into individual step-vectors (using oscillatory head-movements to recognize single steps).

Based on the step-vectors, the blind-walking mean angle was calculated for each participant, which is the average (unsigned) direction deviation per step related to the preceding step in degrees, thus reflecting how straight a participant walked on average. Additionally, the blind-walking angle sd was calculated for each participant, which is the sample standard deviation of the step deviations, a measure that has previously been reported to be related to curvature sensitivity (Kallie, Schrater and Legge, 2007).

Interoception (Heartbeat detection task)

Quantifying interoceptive sensitivity is most commonly done in tasks, during which participants are asked to track or detect their own heartbeats. The heartbeat detection task deployed here generally follows the procedures proposed by Kleckner *et al.* (2015). Participants were connected to a three-electrode electrocardiogram (ECG) using an e-health sensor platform (e-Health Sensor Platform V2.0 for Arduino and Raspberry Pi). The participants were asked to feel their pulse on the wrist and were presented with the two conditions of the heartbeat detection task. In the synchronous condition, an acoustic signal is played 200ms after an R-spike in the ECG, which has been shown to be perceived as simultaneous with the felt heartbeat in the body (Wiens and Palmer, 2001). In the asynchronous condition, a delay of 500ms is added between an R-spike in the ECG and the playback of the acoustic signal, which had been shown to be perceived as not synchronous with the felt heartbeat (Wiens and Palmer, 2001). After participants had experienced the difference between the two conditions while feeling their pulse, the heartbeat detection task began. While sitting upright on a chair without leaning on the backrest and with the hands placed on the legs (palms facing upwards) the participants were presented with 10 seconds of either a synchronous or asynchronous playback. Participants were instructed to feel their heartbeat and to identify whether a synchronous or asynchronous playback had been presented. After the verbal response was given to the experimenter, the next trial was started. In total each participant completed 40 trials balanced for synchronous and asynchronous conditions (in randomized order), with a short (approx. 2 minutes) break after 20 trials. The heartbeat detection task was created and presented using the software ExpyVR (http://lnco.epfl.ch/expyvr).

Each participant's interoceptive sensitivity was calculated, which is the percentage of correct responses in the heartbeat detection task.

Somatosensory amplification

Participants completed the SSA scale questionnaire, which has 10 items scored from 1 to 5 (Barsky, Wyshak and Klerman, 1990). For each participant, the SSA score was calculated as the sum of the scores for the single items.

7.2.4 Statistical analysis

Outlier removal was conducted for all tasks based on the median absolute deviation. Data points in each variable were classified as outliers if they were located further from the median than three times the median absolute deviation, an approach considered a very conservative outlier detection measure (Leys *et al.*, 2013). This outlier removal procedure resulted in the loss of seven data points of a total of 476 data points (in four participants the interoception task could not be performed because no reliable heartbeat signal could be obtained). To inspect the correlations among the included variables, a correlation matrix was created using Pearson correlation coefficients.

Before examining the performances in the perceptual-cognitive tasks, we made a univariate assessment of the effects on redirection thresholds of gender, curvature direction, education, weekly gaming hours and weekly sports hours. These potential confounders were then combined into a basic linear mixed model, which included participant ID as a random intercept and redirection threshold as the target variable.

We tested each of the eight perceptual-cognitive task variables for a possible relation with redirection thresholds by adding them to this basic model without any of the other perceptual-cognitive variables (linear mixed model: redirection threshold ~ gender + curvature direction + education + sport/week + gaming/week + (1 | participant) + tested variable). These models for an individual assessment of the perceptual-cognitive variables are from here on still referred to as "univariate models", although the above listed potential confounders remained included. Eventually a final model was fitted (from here on referred to as the "multivariate model") using a forced-entry approach, meaning all factors and variables were included. In order to compare the effects between variables, standardized coefficients were calculated for the multivariate model. Confidence intervals based on parametric bootstrapping were computed for all coefficients.

Residual analysis of the used linear mixed models was performed by inspecting the associated Tukey-Anscombe plots and the Q-Q-plots of the random factor and the residual error. No transformations of the data were applied. All statistical tests were performed using the software R (R Development Core Team, 2008) with a significance level of $\alpha = 0.05$ (statistical significance was always assessed in a 2-sided fashion). Fitting of the mixed linear models and testing of the coefficients was conducted using the "lme4" and "lmerTest" package (Bates *et al.*, 2015).

7.2.5 Data availability

The datasets generated and/or analysed during the current study are available in the Open Science Framework repository (project title: "Visual Capture of Gait During Redirected Walking"; https://osf.io/5dmkb/).

7.3 Results

Descriptive statistics, the final number of data-points per variable, and the correlations between the included variables are presented in Table 2.

The participants' mean redirection threshold (taking the average of the left- and rightward curvature threshold per person) is a curvature gain of 0.105, which corresponds to a curvature radius of 9.55m (95%CI: 8.78m – 10.48m).

		N	Mean (s.e.m.)	1	2	3	4	5	6	7	8
1	*Rod-and-frame mean angle*	58	4.78° (0.34)								
2	*Vection mean onset time*	60	17.79s (0.83)	.05							
3	*Vection mean strength*	60	39.29 (2.89)	**.28***	**-.45*****						
4	*Romberg quotient*	58	1.19 (0.02)	-.22	-.22	.05					
5	*Blind-walking mean angle*	58	0.58° (0.06)	.22	-.21	.15	-.05				
6	*Blind-walking angle sd*	59	1.89° (0.05)	-.11	-.16	.01	-.08	-.13			
7	*Interoceptive sensitivity*	56	0.55 (0.01)	-.10	.08	-.05	.04	-.05	.05		
8	*Somatos. amplif. score*	60	30.72 (0.59)	.05	-.24	.22	-.05	.19	.18	.15	

Table 2: Correlation matrix of all tested variables, listing descriptive statistics (sample size, mean, standard error of the mean) and the Pearson's correlation coefficients. Statistical significance (two-sided) is represented as: * = $p < 0.05$, *** = $p < 0.001$.

The results from the multivariate and the univariate models, assessing the relation of redirection thresholds with the perceptual-cognitive task performances, are listed in Table 3. In the univariate assessment, gender showed a significant effect ($b = -0.022$, $p = 0.016$), with men having lower redirection thresholds than women. None of the other potential confounders showed any significant effect. Of the perceptual-cognitive variables, the rod-and-frame mean angle ($b = 0.006$, $p = 0.002$), the Romberg quotient ($b = -0.078$, $p = 0.017$) and vection mean onset time ($b = 0.002$, $p = 0.037$) showed significant effects in the univariate models. In the multivariate model, the rod-and-frame mean angle (std.b = 0.324, $p = 0.019$) remained to be a significant predictor of redirection thresholds. Of all included variables in the multivariate model, the rod-and-frame mean angle showed the largest standardized coefficient.

Fig. 5 shows the relationship between individuals' redirection thresholds (taking the average of the left- and rightward curvature threshold per person) and the rod-and-frame mean angle.

	Univariate			Multivariate		
	Coefficient	**P-value**	**95% CI**	**Stand. coefficient**	**P-value**	**95% CI**
Gender (male)	-0.022	**0.016***	-0.040 -0.004	-0.41	0.104	-0.905 0.134
Curvature direction (right)	0.005	0.344	-0.006 0.016	0.17	0.199	-0.092 0.424
Education	0.002	0.124	-0.001 0.004	-0.10	0.497	-0.379 0.200
Sport per week	-0.002	0.145	-0.005 0.001	-0.12	0.321	-0.350 0.117
Video-gaming per week	0.000	0.816	-0.002 0.003	-0.00	0.990	-0.289 0.321
Perceptual-cognitive variables						
Rod-and-frame mean angle	0.006	**0.002****	0.002 0.010	0.32	**0.019***	0.066 0.611
Vection mean onset time	0.002	**0.037***	0.000 0.003	0.20	0.164	-0.110 0.472
Vection mean strength	0.000	0.513	-0.000 0.001	0.17	0.190	-0.078 0.410
Romberg quotient	-0.078	**0.017***	-0.138 -0.017	-0.16	0.202	-0.421 0.073
Blind-walking mean angle	-0.009	0.344	-0.029 0.009	-0.08	0.479	-0.334 0.140
Blind-walking angle sd	0.011	0.312	-0.012 0.033	0.11	0.377	-0.148 0.360
Interoceptive sensitivity	0.033	0.536	-0.078 0.126	0.05	0.635	-0.176 0.317
SSA score	-0.002	0.089	-0.004 0.000	-0.20	0.122	-0.412 0.035

Table 3: Results from the univariate models and the multivariate model, testing the relations of the assessed variables with redirection thresholds. Statistical significance (two-sided) is represented as: * = $p < 0.05$, ** = $p < 0.01$.

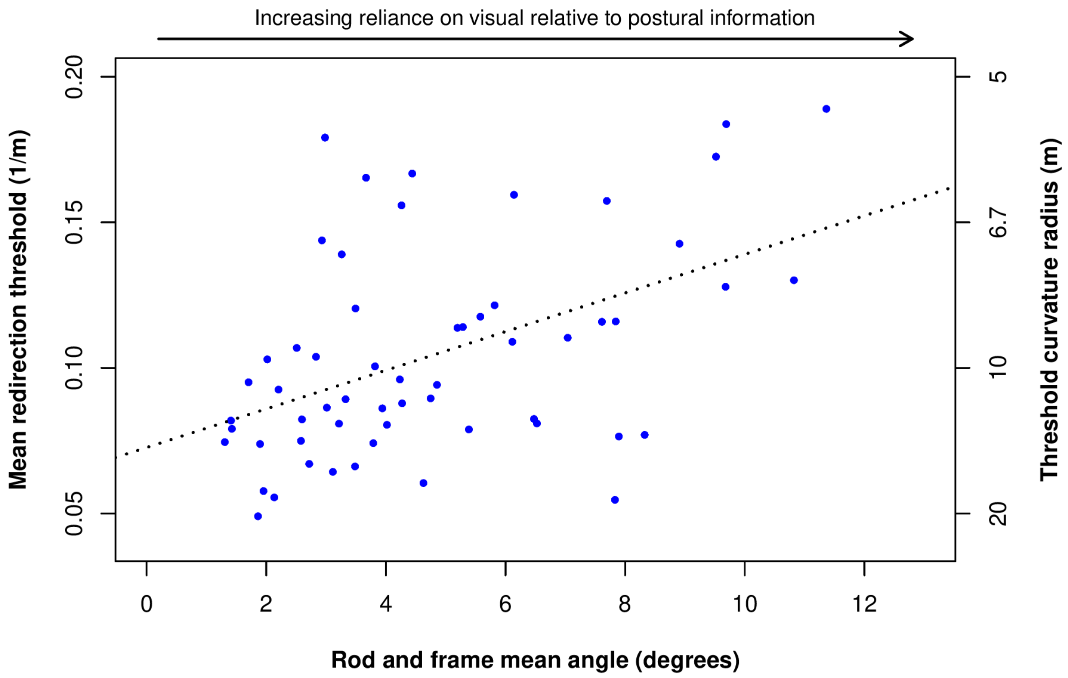


Fig. 5: Mean redirection thresholds plotted against the variable rod-and-frame mean angle. Mean redirection thresholds are given in gain units and the corresponding curvature radii. The regression line is shown (R^2=0.23, p=0.0002).

7.4 Discussion

We set out to determine participants' redirection detection thresholds and the factors of the visual-vestibular (and proprioceptive) integration process that best predict these thresholds. To this end we assessed in 60 healthy volunteers, (1) their redirection thresholds in a VE, and (2) their performances in a series of tasks that quantify the reliance on visual cues during visual-vestibular conflicts and the non-visual monitoring of locomotion, balance and one's internal bodily state.

On average, participants noticed a curvature radius of 9.55m. This finding lines up well with existing results from previous redirection threshold studies, in which curvature radii between 5m and 22m were reported (Steinicke *et al.*, 2010; Grechkin *et al.*, 2016). Other studies that also introduced multisensory conflicts during walking, particularly in the field of agency, reported thresholds in terms of angular drifts instead of curvature radii (Kannape *et al.*, 2010). Although there are differences between the manipulation methods used in redirection and agency studies, as outlined in the Introduction section, a conversion of an angular drift to a curvature gain is conceivable. Under the assumption that users correct for an angular drift by walking on a curved pathway, initially facing the virtual target, the radius of that curvature and thus the corresponding curvature gain can be calculated. Following this conversion, the reported agency thresholds for human walking of 10 to 15 degrees angular deviation over a distance of 1.5m (Kannape *et al.*, 2010), can be expressed as curvature gains of 0.24 to 0.36. Interestingly, this gain range seems to be rather high compared to the threshold gain found in our study. This would suggest that a stronger manipulation is needed to lose the feeling of agency over walking compared to detecting redirection, which agrees with existing findings from hand-based visuomotor incongruency tasks (Asai and Tanno, 2007; Synofzik, Vosgerau and Newen, 2008).

Regarding the cognitive and perceptual tasks, our univariate analyses revealed that individual redirection thresholds were related to the performance in three tasks measuring the subjective visual vertical, illusory self-motion while observing optic flow and the extent to which balance can be maintained in a visually-guided condition relative to a blind condition. We proceed to discuss these findings in turn.

Subjective visual vertical

We used the rod-and-frame test as the classical procedure to measure visual dependency in adjusting the subjective visual vertical. The extent, to which a sitting individual's perception of verticality is influenced by a visually presented distractor frame, is taken as an indicator of his or her reliance on visual relative to postural cues. We found this relative reliance to be associated with participants' redirection thresholds in that the less visually dependent a person is in estimating the subjective visual vertical, the less easily he or she was tricked by the redirection manipulation. For the neuroscientific study of gait and agency, this indicates that the interplay between postural and visual processing even outside the context of locomotion can be taken as a proxy to investigate the complex control of walking, both covert and overt (Kannape *et al.*, 2010). For the VR community, a practical consequence of this finding could be that newly developed techniques of redirection should be evaluated in light of participants' performance in a brief but standardized assessment of the subjective visual vertical.

We found a gender effect in the rod-and-frame test performance, consistent with numerous previous reports (Epting and Overman, 1998; Abdul Razzak *et al.*, 2014). Men were more accurate (i.e. less field-dependent) than women (Wilcoxon rank sum test: W=274, p=0.022). It may thus not be a surprise that, as a group, men also showed lower redirection thresholds in the VR setting, a finding to our knowledge not previously reported in literature. Men's superior performance in both the adjustment of the visual vertical and the judgement of presence/absence of an imposed locomotor perturbation can theoretically be accounted for by two different mechanisms. Either it is a consequence of their generally better spatial abilities (Voyer, Voyer and Bryden, 1995) or it is due to sex differences in graviception (Tremblay, Elliott and Starkes, 2004; Tremblay and Elliott, 2007), which may themselves rest on the anatomy of the otolithic system reportedly to be different for women and men (Sato, Sando and Takahashi, 1992). Whatever the ultimate reasons are for the gender effects found in the present study, they may indicate that the gender differences in the use of VR will remain a tangible reality (https://www.huffingtonpost.co.uk/ailsa-wakley/women-in-vr_b_15403772.html, last accessed April 18, 2018).

Illusory self-motion

Vection susceptibility has long been known as a measure of visual dependency in visual-vestibular interactions (Kim *et al.*, 2015). We assumed that those participants with high vection susceptibility (i.e. participants with small vection onset times and/or high vection vividness) would show a poor awareness of any imposed redirection while walking. However, this assumption was not confirmed by our study. On the contrary, our experiment produced significant results in the opposite direction: Participants with smaller vection onset times, who accordingly were experiencing the illusion of vection faster, were performing better at detecting redirection in the VE. Maybe our assumption that these participants would also be those being more dependent on visual cues was not justified. Note that there was no significant correlation between visual dependency as established by the rod-and-frame test and the vection onset-time. The absence of a correlation between the two measures might be explained by the different natures of the rod-and-frame task and the vection measurement. While the rod-and-frame task assesses visual dependency specifically in relation to postural information under rather static conditions, the vection test examines visual dependency in relation to perception of self-motion using more dynamic visual stimuli. We also note that the subjectivity of vection measurement is a frequently cited methodological drawback, and more objective measures of vection susceptibility are still missing (Palmisano *et al.*, 2015). Perhaps participants with short vection onset times were simply better in experiencing the illusion because of a more rapid visual-vestibular integration. In the VR setting, this integration advantage may have led to a better detection of the redirection manipulation.

We emphasize that illusions of self-motion are not as easily elicited in an HMD, than under conditions of full-field optic flow observed in an optokinetic drum (Kim *et al.*, 2015), due to its smaller field of view. This may have prevented us from uncovering gender effects reported occasionally for non-computerized tests of vection (Darlington and Smith, 1998). In fact, a recent study on vection induced by optic flow in an HMD has likewise described an absence of gender effects in circular vection (Wei *et al.*, 2017).

Visually-assisted postural stability

Standing as still as possible does not guarantee absence of measurable body sway. We focused on this kind of unintentional sway under two conditions: Blind versus fixating on a visual target. The Romberg quotient (ratio between sway without and sway with visual control) is a measure routinely used in neurological assessments of postural stability (Lê and Kapoula, 2008). Again, we expected participants who are less visually dependent in balance control, i.e. whose Romberg quotient is close to 1, to be more sensitive to detect being redirected while walking toward a visual target. And again, like in the case of vection, our findings are opposite to this prediction. The more a participant profited from visual guidance, the lower was his or her redirection threshold. In order to elucidate the counter-intuitive direction of the observed relationship, we correlated individual Romberg quotients and the sway path length observed under eyes-closed and under eyes-open conditions. We found that the Romberg quotient was highly correlated with the total sway path length in the former condition ($R = 0.57$, $p = 2.4 * 10-6$) and weaker with the sway path length in the latter ($R = -0.34$, $p = 0.008$). This raises doubt in traditional interpretations of the Romberg quotient as primarily reflecting the ability to dampen sway by visual information. It rather suggests that the size of the quotient is a more direct function of body sway in the absence of vision. Blind sway also showed a significant negative relation with redirection thresholds when tested univariately ($b = -0.0004$, $p = 0.038$), but no significant effect was found for visually guided sway ($b = 0.000$, $p = 0.96$). This indicates that a lower postural balance stability is associated with a better ability to detect redirection. One possible explanation for this association is that participants with relatively poor balance control are also those, who are more easily thrown out of balance by even small curvature gains. Even if only post-hoc, this interpretation should be tested in future work by assessing body sway during locomotion in a VE with various forms of redirection.

Previous studies have reported correlations between visual dependency in the rod-and-frame test and postural stability. Specifically, reliance on visual cues in the rod-and-frame test were associated with a worse postural stability in balance tests (Isableu *et al.*, 1997, 1998). No such correlations were found in the present dataset. Also, vection strength has been described as positively correlated with the Romberg quotient (Palmisano *et al.*, 2015), but again these two parameters showed no correlation in the present experiment (see Table 2).

Task performances unrelated to redirection thresholds

The tasks introduced under “Blind locomotion control and interoceptive awareness” (Table 1) produced results that were uncorrelated with participants’ redirection thresholds. In what way could the absence of a statistical relationship inform us about the nature of the investigated associations? The results provoke the assumption that an individual’s sensitivity to redirection manipulation barely depends on his or her tendency to veer to either side when attempting to walk blind on a straight path. This sensitivity is also unlikely to be a function of an individual’s interoceptive abilities.

In view of our tentative explanation with respect to the association between blind postural control and redirection thresholds (see above), it may seem puzzling that similar arguments would not also hold for keeping a straight path during blind walking. More particularly, once we assume that persons with an unstable postural control would recognize even small amounts of artificially imposed gait perturbations especially fast, should we not also assume this for persons with an unstable “straight-walking” tendency? Not necessarily. Veering as a dynamic process during locomotion is hardly comparable to balancing as an act of keeping a static body position. Accordingly, balance and veering measures were clearly uncorrelated in the present sample. Notably, a previous study has shown one parameter of veering to be associated with the ability to recognize an experimenter-induced curvature while attempting to walk straight ahead (Kallie, Schrater and Legge, 2007). The authors did not find support for their original hypothesis of an association between spontaneous blind veering and the detection of forced path curvature during blind locomotion (in a 2AFC task; forced leftward or forced rightward). However, they incidentally found that the variability of direction from one step to the next during spontaneous, not redirected locomotion would predict accuracy of curvature detection (higher variability associated with worse detection). They concluded that this variability could form a source of vestibular or proprioceptive information that could be used to assess the presence or absence of non-self-generated gait deviations. We have analysed the relation between participants' redirection thresholds and their step-direction variability in the veering task and found it far from significant. This non-replication of Kallie *et al.* (2007) may be explained by differences in the two procedures: In their experiment redirection was accomplished by a guiding handle during blind walking, while in the present experiment we used a rotation of the visual scenery on the HMD.

Interoceptive sensitivity, assessed with the heartbeat detection task, was examined as a further measure of non-visual body awareness. We assumed that a better monitoring of one's internal bodily state would be associated with a better detection of being redirected. No significant correlation emerged, however, between participants' cardiac awareness and their redirection thresholds. A word of caution is needed about the suitability of the heartbeat detection task for the present context. Although, as a group, participants were able to distinguish between synchronous and asynchronous conditions, performance was not overwhelming (mean success rate: 54.7% against a chance rate of 50%). On an individual basis only 5 out of 56 participants (in four participants the interoception task could not be performed) achieved a performance statistically better than chance. A less difficult interoceptive task may have produced a different result. However, also individual scores on the somatosensory amplification scale reflecting sensitivity to bodily signals were uncorrelated to curvature detection in the VE. Together, these null findings in cardiac monitoring and questionnaire-based interoceptive sensitivity make it improbable that awareness of gait distortions heavily relies on interoceptive variables.

Conclusions

The most prominent relation to redirection thresholds was found in participants' adjustments of the subjective visual vertical. In fact, the performance in the rod-and-frame task was the only variable that remained a significant predictor of individual redirection thresholds in the multivariate analysis. This makes us conceive redirection manipulations in VR as a "visual capture of gait". That is, VR users are made believe their eyes to the extent that their locomotor apparatus and vestibular system are duped. However, on top of this visual-dominance effect, some higher-order sensory integration processes may also influence a person's sensitivity to notice an imposed alteration of gait direction. The associations we found between participants' behaviour in the VR setting and the detection of self-motion and visual-assisted postural stability suggest that those, who achieve an especially rapid visual-vestibular integration are also those with particularly low redirection thresholds. It remains to be investigated how visually more sophisticated VEs than the one used in the present study influence the pattern of findings reported here.

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Author Contributions Statement

All authors participated in conceiving the study. A.N and Y.R implemented the experiments, collected and analysed the data. Y.R wrote the manuscript. All authors reviewed and approved the final manuscript.

8 Segment 1, study 2: **Individual differences and impact of gender on curvature redirection thresholds**

Abstract

To enable real walking in a virtual environment (VE) that is larger than the available physical space, redirection techniques that introduce multisensory conflicts between visual and non-visual cues to manipulate different aspects of a user's trajectory could be applied. When applied within certain thresholds, these manipulations could go unnoticed and immersion remains intact. Research effort has been spent on identifying these thresholds and a wide range of thresholds was reported in different studies. These differences in thresholds could be explained by many factors such as individual differences, walking speed, or context settings such as environment design, cognitive load, distractors, etc. In this paper, we present a study to investigate the role of gender on curvature redirection thresholds (RDTs) using the maximum likelihood procedure with the classical two-alternative force choice task. Results show high variability in individuals' RDTs, and that on average women have higher curvature RDTs than men. Furthermore, results also confirm existing findings about the negative correlation between walking speed and curvature RDTs.

8.1 Introduction

It has been shown that the most immersive way to explore a VE is to really walk in it (Usoh *et al.*, 1999). However, the problem with real walking arises when the VE is much larger than the available physical space. A solution to this problem was proposed where a sensory conflict between the visual information provided through the head mounted display (HMD) and non-visual information (vestibular and proprioceptive) is introduced (Razzaque, Kohn and Whitton, 2001). This conflict, quantified as redirection gain, results in different virtual and real trajectories, for example: the user walks on a different path curvature in real life than in the VE (curvature redirection), the user walks slower or faster in real life than in the VE (translation redirection), and the user rotates slower or faster in real life than in the VE (rotation redirection). Nevertheless, there is a limit to this sensory conflict, beyond which it is noticeable to the user and a break in immersion occurs. Research effort has been spent on identifying this limit, so-called threshold. However, results found by different groups have quite high variance. For example, curvature thresholds found by different research groups vary considerably: 5 m (Grechkin *et al.*, 2016), 10 m (Nitzsche, Hanebeck and Schmidt, 2004) and 22 m (Steinicke *et al.*, 2010). An explanation for this high variance could be that these experiments had different setups and did not control for factors that affect the thresholds such as speed (Neth *et al.*, 2012) or environment design (Hodgson, Bachmann and Thrash, 2014). However, one significant factor could be the high variance in individuals' ability to detect the sensory conflict. This ability has been proposed to correlate with one's visual dependence (Nguyen *et al.*, 2016). More specifically, stronger reliance on visual information could lead to higher threshold for detecting this conflict. Since a number of past research has reported gender difference in visual dependence, it could be hypothesized that there is also gender difference in the ability to detect the multisensory conflict introduced during redirected walking.

8.1.1 Related work

In different tasks related to spatial ability, it has been shown that women tend to have higher visual dependence than men. In a rod-and-frame test where subjects have to align a rod in a tilted frame to the gravitational vertical axis, women are more affected by the frame orientation (Tremblay, Elliott and Starkes, 2004; Barnett-Cowan *et al.*, 2010). In an optokinetic drum, women perceive self-motion induced by a rotating pattern, so-called vection, faster and with stronger intensity (Kennedy *et al.*, 1996; Darlington and Smith, 1998). In the context of redirected walking, there has been research effort to investigate the effect of gender on RDTs (Bruder *et al.*, 2009). Even though no significant effect of gender on RDTs was found, they remarked that the number of subject was too small. Additionally, walking speed was not controlled in their experiment, which may have lead to additional noise in the result.

Given the well established gender difference in visual dependence and the limitations in terms of sample size and controlled factors of the existing study, we performed a larger scale study to investigate the effect of gender on curvature RDTs where walking speed is controlled. We also investigate if the effect of walking speed on curvature RDTs could be reproduced using a non-visual method of speed regulation. Different protocols for threshold identification are also discussed.

8.2 Methodology

8.2.1 Threshold identification

Threshold identification refers to the process of identifying the stimulus level at which a user can correctly detect the stimulus a predefined percentage of the time, e.g. 75%. The result from such detection task is conventionally modelled as a psychometric function, which describes the relationship between the stimulus level (x-axis) and the chance of a certain response (y-axis). Depending on the question posed to the user, there are two types of psychometric functions. In a yes/no task, the user is exposed to one stimulus per trial and is asked the question: “Did you detect the stimulus?”. The y-axis of the psychometric function in this case represents the percentage of “yes” responses, ranging from 0 at zero stimulus level to 1 at significantly high stimulus level. In a classical two-alternative forced-choice task (2AFC), the user is presented two options concurrently or sequentially in 2 intervals, only one of which contains the stimulus, and answers to the question: “In which interval was the stimulus present?”. In this case, the y-axis of the psychometric function represents the percentage of correct responses, and ranges from 0.5 at zero stimulus level to 1 at significantly high stimulus level. Existing RDTs studies employed a variant of the classical 2AFC method where alternative questions such as: “Did you walk to the left or the right?” were presented. The psychometric curve derived from this variant is similar to the one from a yes/no task, where the y-axis ranges from 0 to 1. Generally, the 2AFC method is preferred over the yes/no method due to the fact that the yes/no method often contains response bias, e.g. a tendency to answer “yes” when the stimulus is not perceivable. Therefore, originally in our pilot study, we employed the same 2AFC variant task as other existing RDTs studies for our experiment. However, one pilot subject consistently experienced the sensation of going left when the gains in both directions are sufficiently small, and thus keeping answering “left”. This resulted in a right curvature radius for his left threshold. From an application point of view, this subject can never be redirected left because his left threshold is a right curve. When the same pilot subject was tested again with the classical 2AFC task, the left threshold were found to be a $\sim$ 13m radius left curve. This finding suggests that the 2AFC variant task is not robust against this type of bias. As a result, for the identification of our curvature RDTs in this experiment, we use the classical 2AFC task. Independent of the task used, the threshold identification process revolves around identifying the psychometric function. There are two main types of methods used for threshold identification.

The first type, the constant stimuli method (CSM), fits the whole psychometric function based on users' responses at a pre-selected range of stimuli. In order to obtain a well-fitted curve, many stimulus levels are required and a high number of repetitions is usually needed at each tested stimulus level. For a threshold identification application, this method may not be very efficient since not the whole curve, but only a certain point on the curve or the slope of the curve is normally of interest. The second type, the adaptive method, tackles the efficiency problem of the CSM by using an adaptive procedure which selects the next stimulus level based on the previous response(s) of the users. This type of method does not identify the whole psychometric function, but only some of its parameters such as threshold, slope, guessing rate, etc. One category of adaptive methods is called the maximum likelihood procedure in which the optimal placement of the next stimulus is determined by fitting a parametric model of the psychometric function using data collected from all previous trials. Depending on stimulus placement strategies, stopping conditions and threshold final estimation methods, there is a wide variety of maximum likelihood procedures, of which the Bayesian method is recommended when only the threshold needs to be identified (Treutwein, 1995).

While the CSM is simpler to implement, more trials are required leading to longer exposure time of the subjects in the VE. Therefore, in our experiment, we adopt a Bayesian method called QUEST (Watson and Pelli, 1983).

8.2.2 Speed regulation

In an experiment by Neth *et al.* (2012), walking speed has been shown to have a negative correlation with curvature RDTs. In that experiment, walking speed was controlled by the subjects following and maintaining a distance to an object moving at constant speed. However, it is not known how such task distracts the users visually from the main task of detecting curvature redirection, and consequently how it affects RDTs. Therefore, in our experiment we control the users' speeds by having them following certain audio step rhythms. Dean studied the energy expenditure of human walking and derived a relationship between walking speed, stepping frequency and height (Dean, 1965). The equation describing this relationship is used for generating the aforementioned step rhythms.

8.2.3 User study

8.2.3.1 Experimental design

The experiment scene contains an empty room with four surrounding walls and a red target located 7.5m from the starting position of the user. Before the experiment, users' heights are collected and their personal step rhythms are generated. Each user has to walk with two speed conditions: 0.75m/s and 1.25m/s (similar to the conditions in (Neth *et al.*, 2012) regulated by the step rhythms. We also identify the left and right thresholds separately for each user, resulting in four threshold values of four psychometric functions to be found per user. Speed and curvature direction are therefore within-subject variables. Using the 2AFC method, in each trial each user walks to the red target two times. In only one of the two walks, a curvature gain is applied such that the subject walks on a curve in real life while seeing that he/she walks straight in the VE. The curvature gain is defined as the inverse of the radius of the curve that the subject walks on. The order is randomized between trials. Four separate "QUESTs" handle the four psychometric functions and calculate the next curvature gain value to be tested for each function.

These four next values are selected randomly to be presented in the next trial. This process is called interleaving, commonly used to reduce training and adaption effect. For each "QUEST", 40 trials are required, resulting in a total of 160 trials per user. During the trials, the process of updating the "QUESTs" with users' responses and computing the next curvature gain value is automated. Users respond to the 2AFC question using a built-in eye tracker.

8.2.3.2 Experimental setup

The experimental setup consists of an Oculus DK2 with a built-in SMI eye tracker and an Intersense IS-1200 inside-out optical tracking system mounted on top, providing 6-DOF positional tracking at 180Hz. A cover is added in front of the headset to prevent users from seeing the floor. The scenes are optimally designed in Unity to run at the HMD's maximum frame rate 75Hz. The whole setup is powered by a backpack-mounted notebook. The available tracking space is 12m x 6m. The users also wear noise cancelling headphones, where the step regulating rhythms are played.

8.2.3.3 Participants and procedure

61 subjects (aged from 18-35 (M=25.1, SD=3.9), 30 male and 31 female, right-handed, with normal or corrected-to-normal vision, no vestibular dysfunction or injured) were recruited through the university market place. The experiment lasted about 90 minutes including instruction and set up time and was divided into two sessions. The subjects were paid 15CHF/hour for their contribution.

In the first session, the subjects were informed about the purpose of the experiment and signed the consent form to participate. Subjects provided basic information such as age, handedness, and gaming hours per week. They also were informed about the risk of motion sickness and filled out Kennedy's simulator sickness questionnaire (SSQ) (Kennedy *et al.*, 1993). The subjects were then shown different screenshots of the experiment scene and given the following instruction: "When the program starts, you will see a starting position. Walk to this position. A scene containing a red target will appear. Wait until you hear the step sound and then start walking in the same frequency as the sound towards the target. When you reach the target, a second starting position will appear. Do the same as before and you will see the red target again. Walk to the target again. After you reach the target, a question will appear on the screen asking you: In which walk were you redirected?. Select your answer (first or second) by looking at it, and look at the confirm button to confirm." After the subjects confirmed that they understood the task, they were given some trial runs. In these trial runs, a curvature gain of 0.2 (corresponding to a 5m radius curve) was used. This value was chosen based on existing research such that it will be perceivable for all subjects and consequently they would get how it feels when being redirected. These trials included both curvature directions and both speed conditions, so that the subjects could get accustomed to following the different step rhythms corresponding to the different speeds. After the subjects finished the trial runs they could start the experiment. The experiment was designed such that the subjects would never be close to a wall if they followed the instructions. Therefore, an experimenter is always there but there is no need for him/her to walk behind the subjects. The subjects could take a break any time they want, but on average the subjects took a break every 20 minutes in each session. After each session, the subjects filled out the SSQ again.

8.3 Results and discussion

Out of 61 subjects, one female subject reported motion sickness after 10 minutes and could not continue. 60 remaining subjects could complete the whole experiment. Two-sample t-tests were conducted to compare the SSQ scores before and after each session.

In both sessions, there was a significant increase in score in the after condition. To investigate the effect of gender on this increase in SSQ score, we fitted a linear mixed model which includes gender as a fixed factor and subject as a random factor: ScoreIncrease $\sim$ 1 + Gender + (1|Subject). Results showed no significant effect of gender on the increase in SSQ score.

For each subject, four threshold values were obtained corresponding to the two speeds and two curvature directions: left slow, left fast, right slow and right fast. The distribution of the 240 obtained threshold values (albeit interdependency between data points as each subject contributes four data points) is shown in Fig. 6, serving only as an overall picture. In general, there is a high variability in curvature gain thresholds, ranging from 0.0237 (equivalent to a radius of 42.2m) to 0.1994 (equivalent to a radius of 5.2m) and a median of 0.0976 (equivalent to a radius of 10.24m), interquartile range 0.07 to 0.1336. To investigate the effect of gender, speed and curvature direction, we fitted a linear mixed model which includes gender, speed and curvature direction as fixed factors and subjects as a random factor. We also included gaming hours per week as a fixed factor to investigate whether gaming experience influences the ability to detect curvature redirection. The full mixed-effect model therefore becomes: Threshold $\sim$ 1 + Gender + Speed + CurvatureDirection + GameHours + (1|Subject). Results show no significant effect of curvature direction on RDTs ($p = 0.2$), indicating that right-handed subjects tend to perform equally well at detecting curvature redirection when the curve is towards either left or right direction. There is also no significant effect of the number of gaming hours on RDTs ($p = 0.6$), which means gamers do not have an advantage over non-gamers at detecting redirection.

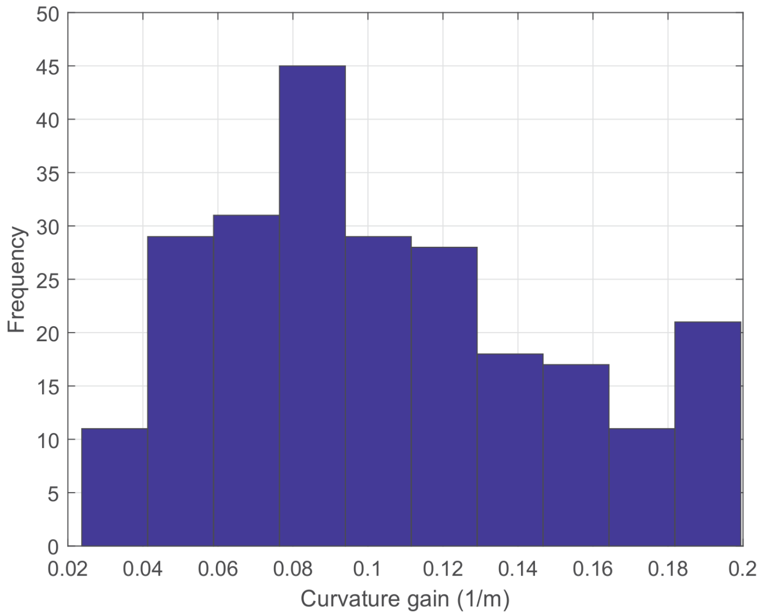

Fig. 6: Distribution of all obtained threshold values

The significant effects on curvature RDTs are speed (Fig. 7a) and gender (Fig. 7b) with $p < 0.001$ and $p = 0.012$ respectively. In Fig. 7, the threshold values were adjusted to isolate the effect of the independent variable of interest while the effects of all other independent variables are averaged. The negative slope in Fig. 7a indicates the faster the walking speed, the lower the curvature RDTs, i.e. higher sensitivity. This result is in line with results in (Neth *et al.*, 2012), although their method of regulating walking speed is different from ours. Finally, Fig. 7b shows that gender significantly affects curvature RDTs, and that male subjects tend to be more sensitive in detecting curvature gain. The average curvature radius threshold for men is 10.7m while it is 8.63m for women. This result also confirms the observed tendency found previously in (Bruder *et al.*, 2009).

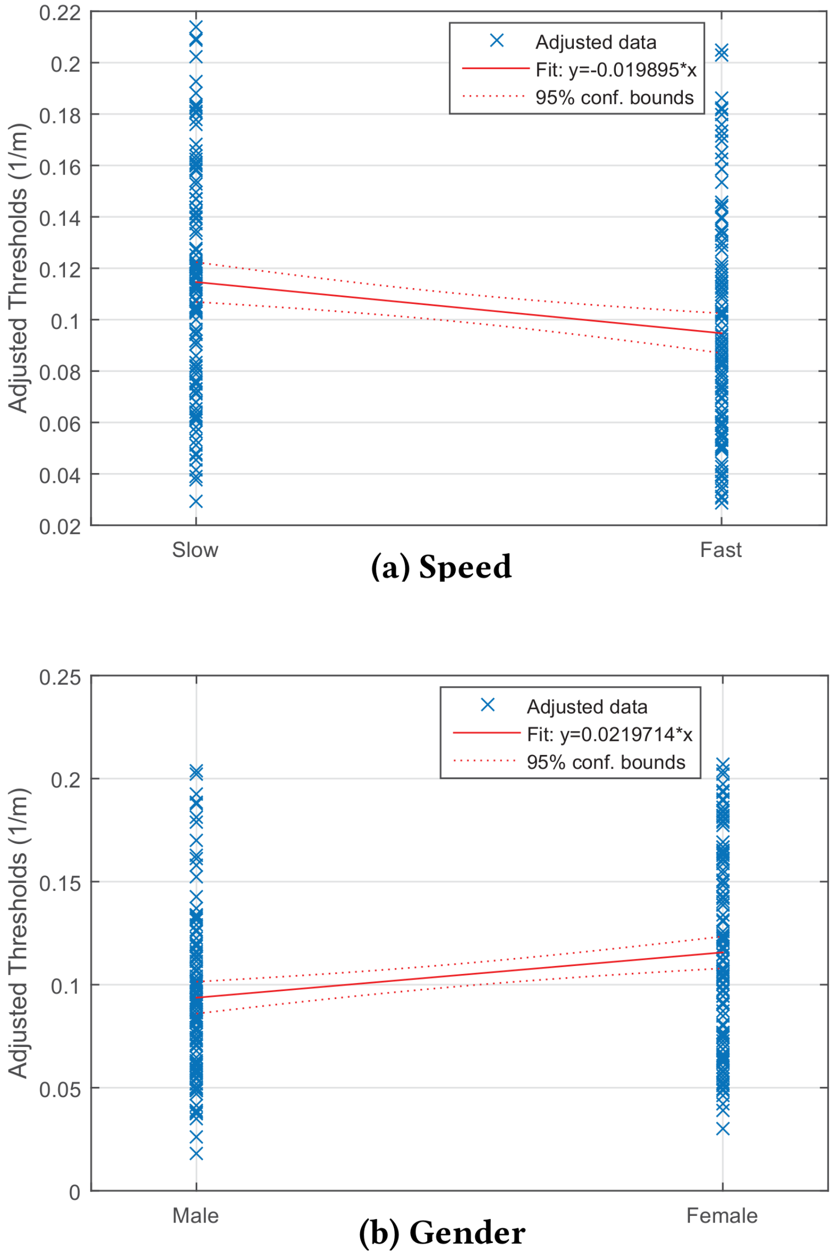

Fig. 7: Effects of Speed and Gender on curvature RDTs

Conclusion

In this paper, we proposed a non-visual method of regulating walking speed using audio step rhythms. We observed that there is a high variability in individuals' curvature gain thresholds. We found that right-handed subjects tend to be equally sensitive to either curve direction and gamers do not have an advantage in detecting redirection. We were able to reproduce existing results on the effect of walking speed on curvature RDTs. Finally, the obtained results supported our hypothesis about gender difference in detecting redirection; we found that men are more sensitive to curvature redirection than women.

The findings from this experiment indicate that curvature gains should be carefully selected for individuals and applied dynamically depending on their walking speed to maintain immersion. Although gender is correlated with RDTs, there is quite high variance in RDTs within each gender. Therefore, a measure of individual visual dependence could potentially be a better predictor for RDTs. Nevertheless, this hypothesis remains to be investigated in future experiments.

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9 Segment 1, study 3: **Effect of environment size on curvature redirected walking thresholds**

Abstract

Redirected walking (RDW) refers to a number of techniques that enable users to explore a virtual environment larger than the real physical space. These techniques are based on the introduction of a mismatch in rotation, translation and curvature between the virtual and real trajectories, quantified as rotational, translational and curvature gains. When these gains are applied within certain thresholds, the manipulation is unnoticeable and immersion is maintained. Existing studies on RDW thresholds reported a wide range of threshold values. These differences could be attributed to many factors such as individual differences, walking speed, or environment settings. In this paper, we propose a study to investigate one of the environment settings that could potentially influence curvature RDW thresholds: the environment size. The detailed description of the study is also provided, where the adaptive, 2-alternative forced choice method is used to identify the detection thresholds.

9.1 Introduction

Compared to walking-in-place, or using navigation devices such as game controllers, real walking in a virtual environment (VE) has been proven to have better fidelity and immersion (Usoh *et al.*, 1999). However, the problem with real walking arises when the VE is larger than the available physical space. A solution to this problem was proposed by Razzaque et al. (Razzaque, Kohn and Whitton, 2001), in which the mapping between the virtual and real trajectories is manipulated. These proposed techniques, quantified as Redirected Walking (RDW) gains, are applied on different aspects of walking such as curvature, translation, rotation.

When applied within certain thresholds, these manipulations are not perceptible and immersion can be maintained. Research effort has been spent on identifying what these thresholds are, however, the thresholds found by different groups have quite high variability.

For example, rotation gain thresholds found by Engel *et al.* (2008) are 0.85 and 1.35 while they are found to be 0.67 and 1.24 by Steinicke *et al.* (2010); curvature gain thresholds found by Hodgson, Bachmann and Waller (2011), Nitzsche, Hanebeck and Schmidt (2004), and Steinicke *et al.* (2010) are also considerably different: 7.64 m, 10 m and 22 m respectively. These thresholds do not seem to be constant and have been observed to vary largely between individuals (Grechkin *et al.*, 2016) and context settings (Hodgson, Bachmann and Thrash, 2014). Correspondingly, it is essential to understand the factors that have effects on RDW thresholds, such that an optimal RDW gain could be applied, maximizing the ”compression” effect of RDW techniques while maintaining immersion.

9.1.1 Related work

Neth *et al.* (2012) conducted a study to investigate the effect of walking speed on curvature thresholds and reported that faster speed increases sensitivity to curvature gain. Regarding the existing work on the effects of environment's design, Steinicke *et al.* (2008) performed a threshold identification study where they presented different visual appearances of the environment and applied textures of different visual density to the environment, consequently generating different amount of optical flow. They found that users tend to be less sensitive to RDW when the amount of optical flow is small. In another study, Paludan *et al.* (2016) varied the number of objects in the scene to investigate the effects of visual density on rotational gain thresholds and could not establish a relationship between visual density and rotational gain thresholds. Considering that high visual density leads to higher optical flow, the two aforementioned studies seem to address the same question about the effects of optical flow on RDW thresholds but their observations are rather contradictory. Given that there are differences in the design of the environments in the two studies, it is not possible to conclude whether optical flow has an effect on RDW thresholds. While investigating the performance of different RDW algorithms in a constrained world, Hodgson, Bachmann and Thrash (2014) remarked that users tended to notice the curvature gains in an aisle more than in a forest. This observation suggests that the dimension of the environment may play a role in the detection of RDW.

Given the aforementioned observations and studies, we would like to perform a study to fill a gap in understanding the effects of environment factors on RDW thresholds: the environment size.

In this paper, we present our experimental design for identifying the effect of environment size on curvature RDW thresholds.

9.2 User study

9.2.1 Experimental design

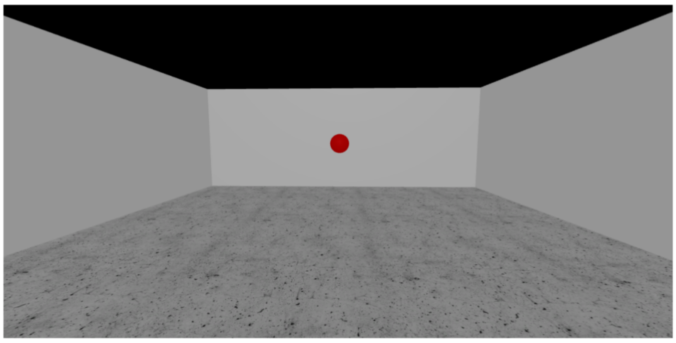
The two scenes, corresponding to two room size conditions, were designed to be as plain as possible to remove any confounding effects of optical flow. Both scenes contain a red target, which is located 7.5m from the starting position of the user, four surrounding walls with simple shading and no texture on the walls. The width of the room in the one condition is 10m, while it is 2m in the other condition. In both conditions, the room length is 10m. Fig. 8 shows the two scenes.

Since it has been found that walking speed affects curvature RDW thresholds (Neth *et al.*, 2012), we control the walking speed of users by asking them to follow certain step sound. The step sound frequency is generated by equation provided by Dean (Dean, 1965). Using the 2-alternative forced choice method, in each trial each user walks to the target two times.

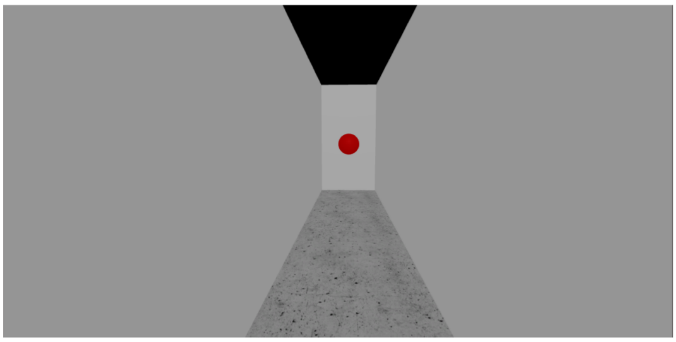
In only one of the two walks, a curvature gain is applied and the order is randomized between trials. The next value of curvature gain to be tested is calculated by a Bayesian adaptive method called ”QUEST” by Watson and Pelli (Watson and Pelli, 1983).

9.2.2 Experimental setup

The experimental setup consists of an Oculus DK2 with a built-in SMI eye tracker and an Intersense IS-1200 inside-out optical tracking system mounted on top, providing 6-DOF positional tracking at 180Hz. A cover is added in front of the headset to prevent users from seeing the floor. The scenes are optimally designed in Unity to run at the HMDs maximum frame rate 75Hz. The whole setup is powered by a backpack-mounted notebook. The available tracking space is 12m x 6m. The users also wear noise cancelling headphones, where the step regulating rhythms are played.



(a) 10m wide room



(b) 2m wide room

Fig. 8: Types of scenes

9.3 Results

60 subjects (30 men, right-handed, with normal or corrected vision) were recruited from the university market place and paid 15CHF/hour for their participation. 30 participants were exposed to the 2m wide room condition and the other 30 participants the 10m wide room condition (same number of women and men tested with each room size condition). To investigate the effect of room size condition (between-subject variable), we fitted a linear mixed model which includes room size as a fixed factor and subjects as a random factor. The full mixed-effect model therefore becomes: Threshold $\sim$ 1 + RoomSize + (1|Subject). Results did not show a significant effect of room size on curvature RDW thresholds ($p > 0.05$).

9.4 Discussion

It was surprising to find that a room's dimension does not significantly affect curvature gain thresholds. This contradicts with the observations by Hodgson, Bachmann and Waller (2011) that their subjects recognized curvature gains more in an aisle compared to an open room. One possible explanation for this finding could be that it is not the room dimension, but the amount of optical flow generated by the scene or the combination of room dimension and optical flow that affect curvature gain thresholds. Since we had no texture on the walls, the amount of optical flow generated in both cases was mostly similar.

It could still be possible that there is a small effect that can not be recovered in a between-subject design since there is a high variability in individual thresholds. A within-subject design where each subjects thresholds are measured in both room size conditions would have been more suitable.

Conclusion

In this paper, we have proposed a study to investigate the effect of environment size on curvature gain thresholds. We found that environment size does not have a significant effect on curvature gain thresholds possibly due to the lack of optical flow. Further study is required to identify which other factors of the environment influence RDW thresholds such that a set of guidelines about how much curvature gain should be applied in a given virtual environment could be obtained.

Acknowledgements

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10 Segment 2, study 1: **The role of perspective and embodiment in redirected walking**

Abstract

Virtual reality (VR) is dominantly applied using a first person perspective (1PP). However, applications using a third person perspective (3PP) raise questions about the processing and experience of different perspectives in VR. Simultaneously, the influence of avatar characteristics on user cognition in 3PP becomes an issue. In the present study the discussion about perspective and the feeling of embodiment over an avatar was expanded to the application of redirected walking. Redirected walking is a method of pathway manipulation in VR enabling the exploration of large virtual environments in confined physical spaces. We examined the sensitivity to redirection depending on the used perspective and avatar movement synchrony. Although no significant effects for the two factors were found, we report a significant relation between the experienced feeling of agency and redirection sensitivity. The finding hints at a possible relation between the concept of embodiment and locomotion monitoring in VR. Furthermore, we confirm previous reports about higher levels of embodiment in 1PP compared to 3PP.

10.1 Introduction

Virtual reality (VR) describes the immersion of users into a virtual environment (VE). There are different devices with which VEs can be presented, ranging from conventional displays, to user-surrounding screens (e.g. CAVE system (Cruz-Neira *et al.*, 1992)), to head mounted displays (HMDs). While each of these methods has its own advantages, HMDs have recently gained popularity and are by most users directly associated with the term VR. Classically, HMDs present VEs through a first-person perspective (1PP). Thus, the VE reacts to head rotations and translations just as the physical environment would react in the real world. The use of HMDs with a 1PP is known to elicit a strong feeling of presence in users (Gorisse *et al.*, 2017). Feeling of presence describes the sensation of being positioned inside a virtual scene. The higher the feeling of presence, the more users have problems distinguishing the virtual scene from reality and react to virtual stimuli as if they were real. This strong feeling of presence opens the door to a range of interesting applications. Especially in the psychological and cognitive sciences, the development in 1PP VR has been observed with great interest. By letting users experience artificial scenarios in a controlled and life-like fashion, psychologists hope to use VR in psychological testing and even treatment of psychological dispositions. For example, applying a virtual confrontational therapy approach, VR has been successfully used in the treatment of anxiety disorders such as fear of heights or phobia of spiders (Garcia-Palacios *et al.*, 2002; Freeman *et al.*, 2018). Additionally, by being able to experience an event through the eyes of somebody else, hopes have been raised to even modulate moral behaviour of users with VR. Studies have shown some success in increasing a feeling of empathy and compassion for out-group members such as for example homeless or elderly people (Oh *et al.*, 2016; Herrera *et al.*, 2018).

One way to even further increase the feeling of presence is by representing the user's body by a virtual avatar (Slater and Usoh, 1994). The term "sense of embodiment" is strongly related to the feeling of presence and describes the extent to which a user identifies with his/her avatar. Kilteni, Groten and Slater (2012) proposed that the sense of embodiment can be separated into three distinct components: 1) The sense of self-location, i.e. the sensation of being located inside a body, 2) the sense of agency, i.e. the sensation of possessing global motor control over a body and 3) the sense of body ownership, i.e. the sensation of self-attribution to a body.

Since combining a virtual avatar with a 1PP can invoke a strong sense of embodiment (Gorisse *et al.*, 2017), it seems that 1PP is the ideal perspective to present VEs via HMDs. However, there have been attempts to apply different perspectives. In third-person perspective (3PP), the avatar is observed by the user from a point of view located elsewhere in the VE. Most often the camera is positioned behind and slightly above the avatar. Conventional gaming application make use of 1PP and 3PP at about similar rates. In VR on HMDs however, 1PP is clearly the dominant perspective and 3PP applications are currently rare. This clear preference for 1PP does not necessarily imply that 3PP has nothing to offer to VR. Although 1PP has been shown to be superior in terms of the evoked sense of embodiment, there is evidence that 3PP can improve spatial awareness and reduce the susceptibility to motion sickness (Gorisse *et al.*, 2017; Monteiro *et al.*, 2018) (see Related

Work section). Given the potential advantages of 3PP over 1PP, it seems possible that more 3PP applications in VR will be developed in the future.

In this study we aim at advancing the investigation of perspective and avatar embodiment by examining their effect on the perception of redirected walking. Redirected walking or redirection is known as a software-based approach to enable the exploration of virtual areas larger than the available physical space (Razzaque, Kohn and Whitton, 2001). This is achieved by distorting the translation of physical movements to the virtual space. For example, a step in the physical world can be turned into a much larger or shorter step in the virtual world (translational gain). Another way of manipulation is the application of a curvature gain. In this case, when a user is moving, the entire VE is rotated around the user, which leads the user to correct for the rotation by walking on a curved pathway. The curvature gain is a key method of redirection to guide users away from physical borders in the room when exploring large virtual worlds. Redirection thresholds describe the intensity with which a redirection gain can be applied until the user notices the manipulation. Ideally, users should not detect redirection in order to maintain the state of immersion.

To our knowledge redirected walking has exclusively been applied in 1PP VR. Here we implement redirection for the first time in 3PP VR and compare redirection detection thresholds between the two perspectives. In addition to the influence of perspective, we examine the effect of avatar embodiment on redirection thresholds (curvature gain). To modulate avatar embodiment we distort the synchrony of avatar and user movements, a technique regularly used in agency research (Nielsen, 1963; Fourneret and Jeannerod, 1998).

10.1.1 Related work

In the VR community a multitude of studies have been performed to empirically elucidate on the differences between 1PP and 3PP in VR. The magnitude of such studies pursue the questions of whether 1) 1PP and 3PP differ in terms of the evoked feeling of embodiment and 2) whether there's a difference in terms of the user's spatial awareness.

While investigating the building blocks of a full body ownership illusion in VR, Maselli and Slater (2013) report that 1PP is superior to 3PP in inducing a feeling of body ownership. Similar conclusions based on subjective reports are reported by other studies (Slater *et al.*, 2010; Galvan Debarba *et al.*, 2017). Interestingly, in the study by Slater et al. (2010), the subjective reports of body ownership are extended by a heart rate measurement. Heart rate deceleration was measured as a reaction to a sudden attack on the personified avatar by another avatar in the scene (slap in the face). In 1PP participants showed a stronger reaction to such an attack than in 3PP. Apart from body ownership, 1PP has also been reported to lead to more agency than 3PP when observing a walking avatar while physically sitting on a chair (Kokkinara *et al.*, 2016). However, not all studies have showed such a clear advantage for 1PP. In (Debarba *et al.*, 2015) no significant difference between 1PP and 3PP in terms of body ownership could be shown. In (Gorisse *et al.*, 2017) 1PP showed higher scores for body ownership than 3PP, but scores for sense of self-location showed no difference between the two perspectives.

While sense of embodiment is mainly examined with subjective measurements, spatial awareness can be assessed by measuring performance in spatial tasks. Gorisse *et al.* (2017) used a virtual projectile deflection task to compare spatial awareness in 1PP and 3PP. In the task, a participant's avatar, located at the centre of a VE, was bombarded with a series of virtual projectiles from different directions. The goal was to deflect as many projectiles with the hands as possible. Although results did not show a significant difference in the rate of deflected projectiles, the time delay until a projectile was perceived was significantly smaller in 3PP. Despite this apparent improvement of spatial awareness in 3PP, a navigation task in the same study revealed an advantage for the first-person perspective. Recent work by Medeiros *et al.* (2018) also finds an advantage for 1PP regarding the performance in a navigation task. Work by Salamin et al., however, showed that users preferred 3PP avatars under certain conditions and that 3PP avatars required less training in a ball-catching task (Salamin *et al.*, 2010). In summary it seems that depending on the nature of the applied spatial task, the increased field of vision in 3PP around the avatar can facilitate performance. 1PP, however, comes off as the superior perspective when it comes to evoking a sense of embodiment in the user.

Apart from the differences in perception due to the used perspective, researches have also examined the relevant properties of the used avatar to induce a sense of embodiment. It has been shown that different aspects, such as for example the avatar's appearance and level of realism, affect the success of a body ownership illusion (Maselli and Slater, 2013). One additional aspect relevant to the ownership illusion is the congruency of performed and visually perceived motor actions. Liang *et al.* (2015) have termed this congruency as "visual agency". Visual agency is a concept often applied in agency research and has been used to determine the limits of agency for various motor tasks (Nielsen, 1963; Fourneret and Jeannerod, 1998; Kannape *et al.*, 2010). It was shown that visual agency improves the sensation of ownership in the rubber hand illusion and can even be used to push the boundaries of the rubber hand illusion (Kalckert and Ehrsson, 2012; W.-Y. Chen *et al.*, 2018).

In VR applications the used perspective and avatar properties have profound influence on the sense of embodiment and spatial awareness of the user. We aim at expanding the outlined work to the study of redirected walking. The detection of redirected walking has been investigated by a multitude of studies and it was shown that apart from walking speed and the VE's appearance, also neuropsychological traits and available cognitive resources affect redirection thresholds (Neth *et al.*, 2012; Bruder, Lubos and Steinicke, 2015; Rothacher *et al.*, 2018). However, so far the used perspective has not been included in the study of redirection thresholds because redirection has only been applied in 1PP. Similarly, the avatar characteristics have also been neglected in the study of redirected walking. The only exception consists of a study by Kruse, Langbehn and Stelnlcke (2018), where the effect of the presence of an avatar was measured on translation gain detection in 1PP. The authors, however, could not find a significant difference between redirection thresholds with or without an avatar.

10.2 Methods

10.2.1 Participants

30 healthy, right-handed participants were recruited (14 women and 16 men, mean age: 25.5 years, SD: 3.3 years). Exclusion criteria included any history of neurological or vestibular disease and any type of injury affecting natural walking. They were mostly recruited through the online marketplace of the University of Zurich. The participants signed an informed consent sheet prior to starting the experiment. All experimental procedures were approved by the Cantonal Ethics Committee of Zurich (BASEC number: 2019-00068) and carried out in accordance with the ethical standards of the Declaration of Helsinki. Participants were paid 15CHF/hour for their participation.

10.2.2 Experimental procedure

The procedure of the experiment consisted of a redirection detection threshold estimation. For each participant the redirection threshold was assessed under three different conditions. The conditions consisted of 1) 1PP redirection, 2) 3PP redirection with synchronous avatar movements, and 3) 3PP redirection with asynchronous avatar movements. Participants wore an HMD and were connected to an Intersense IS-1200 optical tracking system for 6 DOF head position tracking at 180 Hz (Foxlin and Naimark, 2003). For body tracking, participants wore a 32 sensor, whole body tracking suit ("Perception Neuron", www.neuronmocap.com).

In the 1PP condition participants started at one end of a 12 m × 6 m tracking area and found themselves in an empty virtual room with a red pillar 7.5 m in front of them (Fig. 9 a). Redirection thresholds were determined in a two-alternative forced choice task (2AFC task). Participants were asked to walk straight into the red pillar for two consecutive trials. In only one of the two trials a leftward curvature gain of a specific intensity was applied. After completion of the two trials, participants were asked to point out in which of the two trials the redirection had taken place. Dependent on the correctness of the answer, the tested redirection intensity was adapted in the next round. In total, each participant completed 25 rounds in each condition. The selection of the tested intensities and the final estimation of the detection threshold, was done using the bayesian-based adaptive threshold estimation procedure QUEST (Watson and Pelli, 1983). QUEST uses a psychometric function to model the probability of giving a correct answer for a specific curvature gain intensity. The psychometric function starts at a guessing rate of 50% for low curvature gains and approaches a perfect detection rate for strong gain intensities. The detection threshold is classically determined as the stimulus intensity correctly detected in 75% of cases.

In the 3PP conditions the threshold estimation followed the same general procedure. However, the participants' virtual point of view during the task was shifted behind and slightly above a virtual avatar (Fig. 20 b). The avatar mimicked the movements of the participants. The task was to steer the avatar straight into the target using real walking. In 3PP, the rotation of the VE due to the applied redirection was centred around the virtual camera through which the participants observed the virtual scene. A curvature gain applied in this setting has the same effect as in the classic 1PP setting. Thus, trying to make the avatar walk a straight virtual trajectory results in the same bending of the participants' physical walking pathway as in 1PP redirection. The virtual camera reacted appropriately to all head movements of the participants. This allowed participants to inspect the surrounding VE in the same manner as in the 1PP condition.

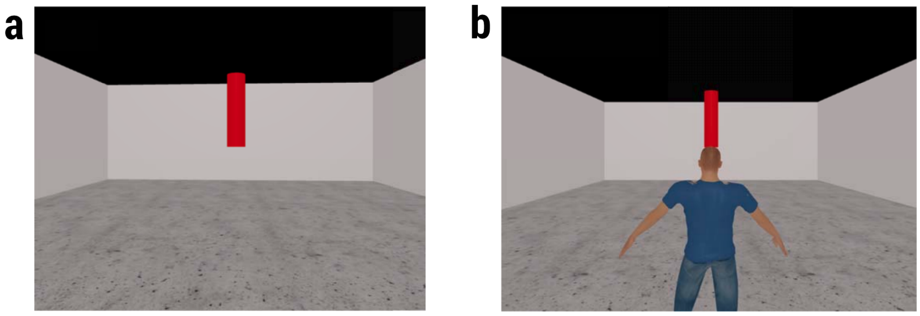


Fig. 9: Virtual scene from the participants' perspective at the beginning of a trial. In the 1PP condition (a) the virtual target is visible in front of the camera. In the 3PP condition (b) a virtual avatar is visible between the camera and the virtual target.

The 3PP conditions consisted of one condition with synchronous avatar movements and one condition with asynchronous avatar movements. In the synchronous condition the avatar copied all body movements of the participants. In the asynchronous condition only changes in the coordinates of the body position were copied. Therefore, the avatar moved forward if the participant moved forward. However, the walking movements of the avatar, i.e. the position of the legs and arms, followed an artificial, generic walking pattern and did not correspond to the participant's walking style. Thus, it was still possible to steer the avatar into the virtual target, but the movements of the individual body parts were not congruent with the avatar's movements.

Each condition took a duration of approximately 30 minutes. The three conditions were conducted in two separate sessions. Before starting each condition, participants completed a short habituation phase (approx. 2 minutes), in which they were accustomed to the virtual body used in the condition. During the habituation participants were encouraged to watch their virtual body and to move arms and legs to see the corresponding virtual movements. In the habituation to the asynchronous 3PP condition the arm and leg movements were not copied and the avatar would move its body parts independently. In addition to the habituation phase, participants performed a short series of training trials before each condition to get used to the redirection procedure. The order of the three conditions was randomized and balanced over participants. In between conditions the experienced feeling of embodiment during the preceding condition was assessed. On a scale of 0 to 100 participants scored the following statements: 1) “I felt like I was in control of the body I was seeing” (agency). 2) “It felt that the virtual body was my own body” (body ownership). 3) “It felt as if my body was located where I saw the virtual body to be” (self-location). 4) “It felt as if I had more than one body” (more bodies). 5) “It felt like I really was in the virtual room” (presence).

In addition, participants scored their feeling of motion sickness before and after each condition using the Simulator Sickness Questionnaire (SSQ) (Kennedy *et al.*, 1993).

10.3 Results and discussion

In the present study we investigated the redirection detection thresholds of 30 healthy participants in three different conditions. The three conditions consisted of a 1PP condition, a 3PP condition with synchronous avatar movements and a 3PP condition with asynchronous avatar movements. The mean redirection thresholds of the three conditions in curvature gains were 0.140 in the 1PP condition, 0.147 in the synchronous 3PP condition and 0.154 in the asynchronous 3PP condition. The mean redirection threshold of 0.14 in the 1PP condition generally agrees with redirection thresholds reported in previous studies (Steinicke *et al.*, 2010; Grechkin *et al.*, 2016). In Fig. 10 the individual redirection thresholds for the three different conditions are presented.

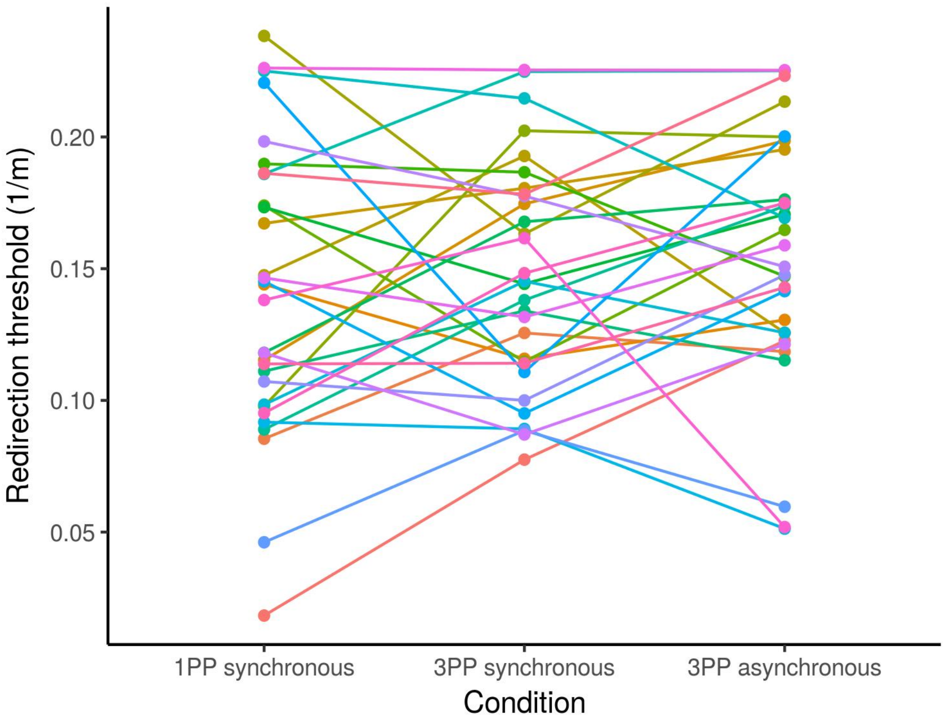


Fig. 10: Redirection thresholds of the three tested conditions. Coloured lines indicate the profiles of the individual participants.

Visual inspection of the graph does not reveal any salient differences between the three conditions. This impression was confirmed in the formal analysis of the data. The data were analysed using a linear mixed model approach. We fitted a model using redirection thresholds as the target variable. As predictors we added a random effect for the participants and a fixed factor for the condition. We added the number of the session (1st/2nd) and the average walking speed to account for their influence (see Neth *et al.*, 2012). In addition, we added the scores of the five embodiment questions as predictors. The final model written out in the notation style of the lme package of the statistical software R (R Development Core Team, 2008; Bates *et al.*, 2015) looks as follows: threshold ~ condition + walkingSpeed + sessionNr + presence + agency + morebodies + selflocation + ownership + (1|Participant). The analysis did not reveal a significant difference between the 1PP condition and the synchronous 3PP condition (b_{1pp} = -0.016, p = 0.168) nor a significant difference between the synchronous 3PP condition and the asynchronous 3PP condition (b_{3pp_async} = 0.003, p =

0.740). Thus, we could neither show an effect of perspective (first comparison) nor an effect of avatar movement synchrony (second comparison) on redirection thresholds. There are different explanations for the absence of the two sought-after effects. Although the condition factor was tested in a within-subject design, the total number of participants was limited to 30 people. The sample size of 30 participants might not contain enough power to uncover the targeted effects. Another possibility is that the use of a 3PP truly does not affect the sensitivity to redirection. For a given curvature gain the walked curvatures are identical in both perspectives. Thus, the demands to notice the manipulation could be equal and independent of the perspective through which the VE is perceived. Similarly, the manipulation of the avatar synchrony might not have been a strong enough intervention to significantly affect redirection thresholds. Since the avatar still followed the general walking direction of the participant even under the asynchronous condition, the feeling of agency was possibly preserved to some degree. A more radical intrusion in the experienced feeling of agency might have affected redirection sensitivity more strongly.

In total, none of the other predictors showed a significant relation with redirection thresholds except the questionnaire score of the feeling of agency ($b_{agency} = -0.0003$, $p = 0.043$). The finding proposes a negative relation between the feeling of agency and redirection thresholds. This implies that the more feeling of agency a participant felt during a specific condition, the better this person detected the redirection (lower threshold equals better detection). One possible interpretation of this finding is that the feeling of agency affected other aspects of perception, such as action monitoring, which led to an altered redirection sensitivity. Such a causal relationship is, however, difficult to base on a correlation, especially in light of the non-significant effect of avatar movement synchrony. The intention behind manipulating movement synchrony was to decrease feeling of embodiment and test its effect on redirection sensitivity. The results of the embodiment questionnaires showed that the participants did report less feeling of agency in the asynchronous 3PP condition compared to the synchronous 3PP condition ($t = 3.01$, $df = 29$, $p = 0.005$). All other questions were not significantly affected by movement synchrony of the avatar. Despite this reduction in agency, no significant effect on redirection thresholds emerged. Thus, the exact relation between the feeling of agency and redirection sensitivity remains unclear at this point. Further, higher-powered experiments are needed to confirm and clarify the here reported findings.

In addition to the analysis of redirection thresholds, an examination of general differences between the first and third person perspective was conducted. These comparisons were performed between the 1PP condition and the synchronous 3PP condition to exclude any influence from an altered movement synchrony with the avatar. The SSQ scores, reflecting the motion sickness, were compared between the two perspectives using a linear mixed model. The used model consisted of the SSQ scores as the target variable and the perspective (1PP/3PP) and the number of session (1st/2nd) as predictors. Participants were incorporated as a random effect (SSQ ~ perspective + sessionNr + (1|participant)). The model revealed no significant difference between the experienced motion sickness between the two perspectives (b_{1pp} = -0.933, p = 0.171). A significant effect of session was revealed, showing a reduced SSQ score in the second session (b_{2nd} = -1.53, p = 0.455). Possibly, participants adapted to the VR exposure to some degree, which would explain the reduction in experienced motion sickness. The two perspectives were also compared regarding the scores of the embodiment questionnaires. Using dependent T-tests, the scores of the five embodiment questions were compared between the two perspectives. No difference between perspectives were found for the feeling of agency (t = 1.62, df = 28, p = 0.116) and the feeling of body ownership (t = -1.56, df = 28, p = 0.131). Feeling of having multiple bodies did show a significant difference between the two conditions. This is not further surprising since in the 1PP condition no feeling of having multiple bodies is expected. Lastly, feeling of presence and feeling of self-location did show significantly higher scores in 1PP ($t_{presence}$ = -3.45, df = 29, p = 0.002, $t_{location}$ = -2.40, df = 28, p = 0.023). Thus, the present experiment coincides with previous studies, reporting higher feeling of embodiment in the 1PP compared to 3PP (Maselli and Slater, 2013).

Conclusion

In the present study we examined redirection detection thresholds in a first and a third person perspective. Additionally, the influence of avatar movement synchrony was assessed in the 3PP condition. Although neither perspective nor movement synchrony showed an effect on redirection thresholds, a significant positive relation between the experienced feeling of agency and redirection sensitivity was found. In addition, participants reported higher feeling of presence and self-location in the 1PP condition compared to 3PP. Currently, VR is still dominated by 1PP applications. However, given the recent emergence of successful 3PP implementations in VR, it is likely that 3PP will find more frequent application in the future. Thus, discussions about the experience of different perspectives and avatar characteristics will become increasingly important. The here reported results contribute to this inquiry while at the same time expanding the discussion to the study of redirected walking. Hopefully, the present study can serve as a stepping stone for future investigations into the implications of perspective and feeling of embodiment for user cognition and VR locomotion.

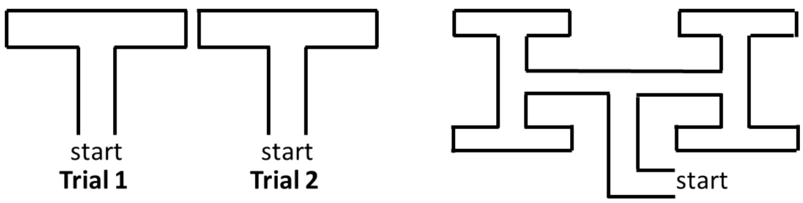
11 Segment 3, study 1: **Spontaneous alternation behaviour in humans**

Abstract

Redirected walking refers to a number of techniques that enable users to explore a virtual environment larger than the physical space by real walking. The efficiency of these techniques has been shown to improve when predictions about the user's future trajectory are incorporated. Predictions can be made not only based on the knowledge about the environment but also on how humans behave in it. In a maze-like environment, it is known that most animal species show a strong preference to alternate their turning direction. This is called spontaneous alternation behaviour (SAB). Although such behaviour has also been observed in humans during maze tracing tasks, little is known whether they also exhibit this behaviour during real walking, and if they do, what their alternation rate is. In the experiment described in this paper, 60 right-handed subjects were invited to walk freely through a virtual maze consisting of a primary 90 degree forced turn followed by three consecutive T-junctions. Results show that, on average, humans exhibited an alternation rate of 72%. When looking only at the junction after the forced turn, subjects alternated with 76%. After two consecutive turns of the same direction subjects alternated with 93%. The alternation rates obtained not only clearly confirm the existence of SAB in humans but also could be used to improve the accuracy of existing prediction models in human walking.

11.1 Introduction

Spontaneous alternation behaviour (SAB) refers to an animal's tendency to avoid consecutive repeated choices when exploring a maze. In a classical SAB test, an animal is placed at the start stem of a T-maze (Fig. 11a) at the beginning of two trials. In each trial, the animal moves through the start stem and enters one goal arm. If in the first trial the animal enters one goal arm, in the second one it will tend to choose the other arm, and thus "alternate", with above chance probability. Although there is numerous research on such behaviour in various animal species, not much has been done on humans, particularly adults. Until 1980, most SAB studies in humans involved children tracing mazes using pen and paper (Harris, 1971), or sequentially pressing two buttons to turn on lights of different colours (Miller *et al.*, 1969). In (Pate and Bell, 1971), preschool children from 3 to 6 years old were asked to crawl across a T-maze tunnel two times, and the average alternation rate was found to be 56.4%, which did not differ from chance. With regards to studies in human adults, in (Lawless and Engstrand, 1960), university students were asked to use a stylus to trace a forced maze (Fig. 11b) blindfolded and results showed that the alternation rate is 75%. The only literature found where SAB was tested on walking adults is (Neiberg, Dale and Grainger, 1970), a study in which college students were asked to walk through a "T-corridor" two times. Their alternation rate was shown to lie at 60%. It is, however, unclear what the exact instructions to the subjects were, and whether they might have affected the spontaneity of their behaviour.



(a) T-maze **(b) Forced maze**

Fig. 11: Types of mazes

At this point, the question may arise why we choose to investigate SAB in humans after years of interrupted research. The answer to this question is twofold. The first reason lies in the development and increasing availability of virtual reality (VR) technology. While it must have been complicated in the 80s to build an apparatus suited for testing SAB in human walking, VR technology opens the door to countless possibilities to build and design various virtual environments at no significant incremental cost. Moreover, the combination of tracking technology and VR allows users to walk naturally in a virtual environment instead of having to stay in place while tracing mazes using a stylus. In order to elaborate on the second reason to study SAB in humans, we would like first to introduce the concepts of redirected walking (RDW) and RDW planners using model predictive control (MPC). RDW refers to techniques that enable the users to explore a virtual environment (VE) larger than the physical space. First introduced in (Razzaque, Kohn and Whitton, 2001), the RDW techniques involve "manipulating" the mapping between the virtual and real space. These techniques are applied on different aspects of walking: translation – the users walk slower/faster in the VE than in real life, rotation – the users rotate slower or faster in the VE than in real life, and curvature – the users walk on a curve in real life while still going straight in the VE. When applied within certain thresholds, these manipulations will go unnoticed and immersion can be maintained (Steinicke *et al.*, 2008; Grechkin *et al.*, 2016). In case of limited physical space, these RDW techniques could be used in different manners to steer users away from the physical boundary, and when these methods fail and collisions still occur, "resets" could be applied to reorient users towards open space (Williams *et al.*, 2007). For example, the steer-to-center, steer-to-orbit, and steer-to-changing-targets algorithms use RDW techniques to steer users toward the centre, a circular path around the centre, and towards one of the predefined points in the physical space respectively (Razzaque, Kohn and Whitton, 2001). On the other hand, the MPC algorithm chooses where users should be directed to, a so-called RDW action, based on the prediction of their next N moves (Nescher, Huang and Kunz, 2014). This RDW action is chosen to minimize a cost function which penalizes the use of resets, therefore the number of resets is also minimized. In (Nescher, Huang and Kunz, 2014), the MPC algorithm was shown to reduce the number of resets by 41% compared to the steer-to-center algorithm in a maze-like environment. The efficiency improvement could be accredited to the usage of users' movement prediction in the planning process. This prediction is expressed as a probability distribution and so far is obtained based on relatively basic assumptions such as: under normal circumstances, users don't walk through virtual obstacles or walls; in a T-maze condition, the probability of turning right or left is 50%; etc. If more knowledge about how users behave is obtained, prediction's accuracy can be improved, consequently enhancing the efficiency of the MPC algorithm. From this angle, we would like to design an experiment to investigate whether humans really exhibit SAB behaviour, and what their alternation rate is if they do. The results of this experiment not only allow us better understanding of how humans behave, but also contribute to the further improvement of existing RDW technology.

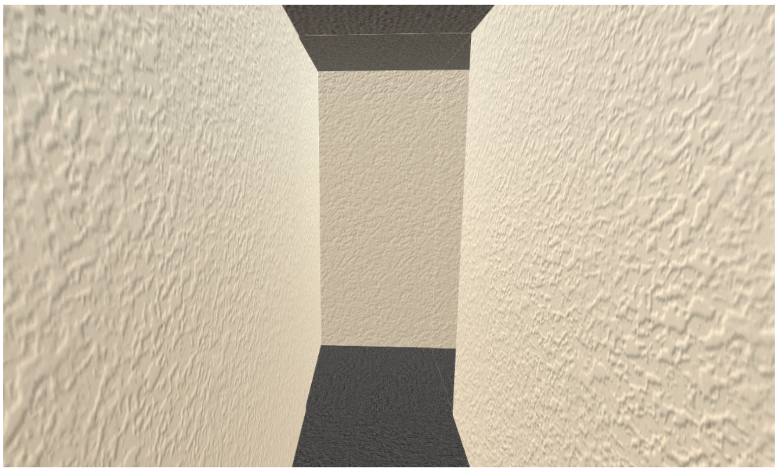


Fig. 12: Maze view from the starting position, before the forced turn

11.2 User study

11.2.1 Experimental design

In the classical T-maze (Fig. 11a), SAB is quantified as the alternation rate, namely the percent of times the subjects alternate turn directions. In an extended forced maze (Fig. 11b), where subjects perform a number of forced turns before the free turns at the T-junctions (Fig. 11b), SAB could be quantified as the conditional probability of alternation given the direction of the previous turn(s).

While both designs are suitable for investigating the existence of SAB, we selected the extended forced maze over the classical T-maze as the environment is more similar to a natural setting. Moreover, an extended forced maze also offers the possibility to observe whether users maintain or change their alternation rate as they walk further into the maze. The final maze design consists of an initial 90 degree forced turn, which is followed by three consecutive T-junctions (Fig. 11b). Unit pieces of the maze such as straight, corner and T-joint are first modelled in Blender and then imported and assembled in Unity. The maze walls have a generic plaster texture (Fig. 12), and lights are placed in the environment such that when the subjects are at the T-intersections, both choices look completely identical. The distance between each turn is 1.5m. Due to limited lab space, the complete maze can not all fit in. As a result, only parts of the environment are shown at a time depending on the position of the subjects. This approach is similar to the flexible spaces approach introduced in (Vasylevska *et al.*, 2013).

Step regulating sound is played during the subjects' walk in the maze to ensure a walking speed of 0.75m/s for all subjects. The height information of subjects was collected before the experiment day, and the step sound prepared in advance using the formula in (Dean, 1965). This fixed walking speed is used to ensure subjects walk continuously through the maze without stopping.

11.2.2 Experimental setup

The experimental setup consists of an Oculus DK2 and an Intersense IS-1200 optical tracking system mounted on top, providing 6 DOF positional tracking at 180Hz. The scene is optimally designed in Unity to run at the HMD's maximum frame rate 75Hz. The whole setup is powered by a backpack-mounted notebook. The available tracking space is 12m x 6m.

11.2.3 Participants and procedure

60 subjects (aged from 18-35 (mean=25.2, SD=3.8), 30 male and 30 female, right-handed, with normal or corrected-to-normal vision) were recruited through the university market place. The SAB experiment lasted about 15 minutes including instructions and set up time. The subjects were not informed about the purpose of the experiment. The direction of the initial forced turn was balanced across subjects. Before starting the experiment, subjects were shown screen shots of different parts of the experiment and were given this instruction: "When the program starts, you will see a starting position. Walk to this position. A maze will appear (Fig. 12) and you will hear ongoing step sounds. Please follow this step rhythm while walking through the maze without stopping. You can freely explore the maze as you want." After signing the consent form, subjects put on the backpack and started walking. An experimenter walked right behind the subjects to prevent them from colliding with the physical walls in the event that they would not follow the path of the VR maze. After the subjects completed the experiment, they were asked: "Did you use any strategy or plan where to go? Or were you just walking spontaneously?" Their answer to this question

determined whether their data would be used for the analysis. Subjects were paid 15CHF/hour for their contribution.

11.3 Results

When asked if they used any strategy for the maze, out of 60 subjects, 11 subjects (8 male and 3 female) answered similar to one of the following ways: “I was trying to see if I can walk in a circle”, “I deliberately changed directions so that I can walk further”, or “I decided to always turn left”. The data from these subjects were not included in the analysis. The remaining 49 subjects answered that they were walking spontaneously without any planning.

The three consecutive direction choices per subject were scored either as alternations or repetitions based on the prior direction choice, or in the case of the first junction, based on the direction of the forced turn. This resulted in three binary data points per subject. There are eight different possibilities for an outcome of a subject (000, 001, 010, 100, 011, 101, 110, 111; 1 = Alternation, 0 = Repetition). The frequencies of those eight outcomes were counted and the overall distribution of walking patterns is presented in Fig. 13. Using a chi square goodness of fit test, this distribution was shown to be significantly different from what would be expected if the subjects had alternated at a chance level ($\chi^2 = 34.76$, $p < 0.001$).

To estimate an overall alternation rate while incorporating the threefold contribution to the dataset by each subject, we fitted a logistic regression to the data, which included subjects as a random factor (model: Alternation ~ 1 + (1|Subject)). Based on the formula of the logistic regression, the estimated intercept of this model is P(alternation) equal to log(P(alternation)/P(repetition)). By looking at the intercept’s confidence interval, we tested whether the intercept is significantly different from zero, which corresponds to an alternation rate of 50% (log(0.5/0.5) = 0). The logistic regression showed an overall estimated alternation rate of 72% (defined as P (X|Y)), which was shown to be significantly different from a 50% alternation rate (95% confidence interval: 0.65 – 0.79). In order to examine effects of gender and the sequential position of the junction (first, second or third junction) we fitted a second logistic regression, which included gender and junction position as fixed effects (model: Alternation ~ 1 + Gender + JunctionPosition + (1|Subject)). The statistical significance of the effects gender and junction position were tested using likelihood ratio tests by comparing the full model to a reduced model missing the factor of interest respectively. The likelihood ratio tests, however, showed no significant effects of either gender nor junction position (gender: $\chi^2 = 0.02$, $p = 0.88$; junction position: $\chi^2 = 0.20$, $p = 0.65$). To specifically test the alternation rate right after the primary forced turn regardless of direction (defined as P (X|FY)) against a rate of 50%, we conducted a binomial test. Results showed that subjects alternated with a rate of 76% , which is significantly different from what would be expected by chance ($p < 0.001$ (two-sided)). Finally we also performed a binomial test on whether the alternation rate after two consecutive turns in the same direction (defined as P (X|YY)) is significantly higher than 50%. The alternation rate following such two consecutive turns was 93%, which is significantly different from what would be expected by chance ($p < 0.001$ (two-sided)). An overview of alternation rates can be found in Table 4. All tests were performed using the statistical software R (R Development Core Team, 2008; Bates *et al.*, 2015) with a significance level of $\alpha = 0.05$.

	$P(R\|FL)$	$P(L\|FR)$	$P(X\|FY)$	$P(X\|Y)$	$P(X\|YY)$
Male (N=22)	0.82 (11)	0.64 (11)	0.73* (22)	0.73* (22)	0.93* (14)
Female (N=27)	0.75 (12)	0.80* (15)	0.78* (27)	0.72* (27)	0.92* (13)
Total (N=49)	0.78* (23)	0.73* (26)	0.76* (49)	0.72* (49)	0.93* (27)

Table 4: Summary of spontaneous alternation rates expressed as conditional probabilities given the prior turn direction(s). P(R|FL) and P(L|FR) are the alternation rates after the first forced left and right turn respectively. P(X|FY) is the alternation rate right after the primary forced turn regardless of direction. P(X|Y) and P(X|YY) are the overall estimated alternation rates after 1 and 2 turns in the same direction respectively. Number of subjects is indicated in brackets. (Stars indicate significant differences to $p = 0.5$, $\alpha = 0.05$)

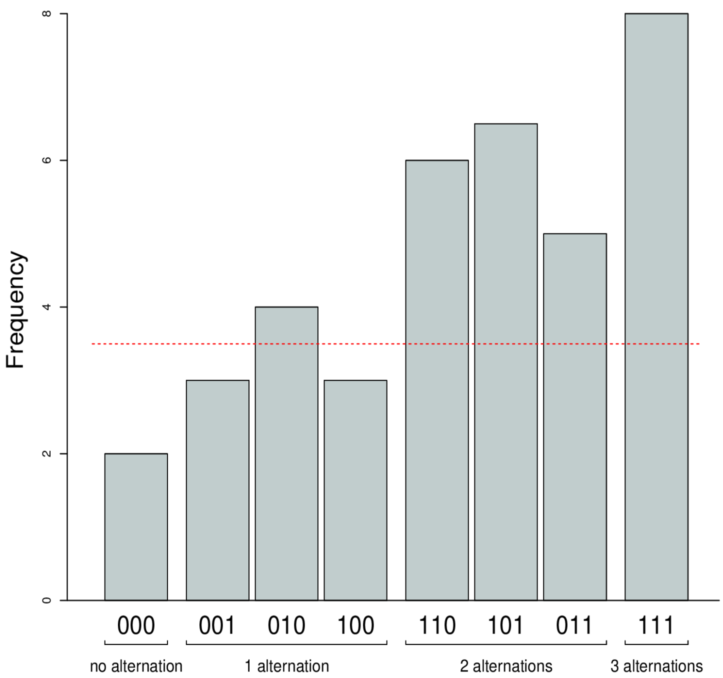


Fig. 13: Distribution of the frequencies of the eight possible maze trajectories (1=Alternation, 0=Repetition). The dashed red line indicates the frequencies expected by an alternation rate of 50%.

11.4 Discussion

Our results indicate that in a maze-like VE, walking subjects alternate directions with a rate around 72%. This alternation rate was shown to be independent of gender and sequential junction position, where the latter finding suggests that the alternation behaviour does not decay or increase over time. Our finding seems to be comparable to alternation rates found when humans are navigating through a stylus maze as in (Lawless and Engstrand, 1960) and surpasses the alternation rate so far found in walking humans (Neiberg, Dale and Grainger, 1970). Additionally we showed that a forced turn, in which subjects don't make a direction decision themselves, still resulted in an alternation rate of 76%. This finding suggests that in the context of SAB it doesn't seem to make a difference for humans, whether a turn direction is self-chosen or imposed. When looking at the distribution of the eight possible maze trajectories in Fig. 13, a clear shift towards trajectories with two or three alternations can be observed. Finally, when looking at junctions after two consecutive left or right turns, subjects changed direction with an even higher rate of 93%. In general, the positive finding of alternation behaviour in walking humans shows potential that this can be used to increase the efficiency of redirected walking using the MPC framework. However, how much of an enhancement the inclusion of an SAB rate would bring is still not clear and requires experimental testing.

Moreover, while the alternation behaviour seemed stable in our setting, it remains to be investigated how SAB can change in slightly different contexts. It was our effort to exclude other factors that might possibly influence alternation behaviour as much as possible for this study: We didn't give the subjects any specific task, for example finding a way out of the maze; we created all junctions completely equal in terms of visual appearances including brightness. When considering more realistic VEs that might come up in real applications, these factors are not suppressed as they were in this experiment. Another point that should be addressed is that the distances between T-junctions in our maze were uniform and relatively short (1.5m). In previous studies with humans, the distance between junctions has been shown to significantly influence alternation rates; longer distances between turns lead to lower alternation rates (Lawless and Engstrand, 1960). Finally, we mostly presented a first level alternation analysis, which assumes that alternation is only dependent on the immediately previous turn. A more in-depth analysis might be required to understand whether earlier turns also have an effect on the current turning choice.

Conclusion

In this paper, we described an experiment to investigate SAB in human adults during walking in a virtual maze. The alternation rate obtained could be used to update existing prediction models, thus enhancing the efficiency of the MPC planner. However, how much performance improvement could be achieved is not yet known, and will require further implementation and benchmarking. It would also be interesting to see if the behaviour is affected when RDW techniques are applied. More specifically curvature gain, which forces the user onto a curved path through the insertion of a small rotation of the virtual scene, might influence the alternation rate in maze-like scenarios. Finally, the experiment is focused on testing SAB in a relative simple setting, without defined tasks, or other factors such as visual information (brightness, moving objects, etc.) and auditory information. The presence of these factors could significantly affect the alternation rate, and therefore requires further research.

12 Segment 3, study2: **Walking through virtual mazes: Spontaneous alternation behaviour in human adults**

Abstract

Spontaneous alternation behaviour (SAB) is the tendency to systematically alternate directional choices in successive maze arms. Originally discovered in rats, SAB has been extensively investigated in a broad range of species. In humans, however, SAB has been mostly ignored, possibly due to the difficulties arising from the use of life-size mazes. We here propose to close this gap by advancing the study of human SAB by use of virtual reality (VR). Alternation rates in humans were examined in three experiments, each deploying a specific type of virtual maze. The three virtual mazes tested 1) the effect of a concurrent cognitive task on baseline alternation rates, 2) the differential influence of locomotor and visual factors on alternation behaviour, and 3) direction alternation in an unrestricted open space. We report a general tendency in adult human walkers to alternate walking directions in the classical T-maze context. The search for an effect of a concurrent cognitive task and the influence of locomotor and visual factors on alternation behaviour remained inconclusive. No evidence for alternation behaviour in an open space was found. Together, the experimental series elucidates the presence and characteristics of SAB in humans and paves the way for the systematic study of its neurocognitive basis.

12.1 Introduction

Spontaneous alternation behaviour (SAB) refers to an animal's tendency to alternate consecutive directional choices while exploring a maze. First demonstrated in rodents (Tolman, 1925), SAB has later been observed in a large number of species across very different taxonomic groups, including vertebrates, invertebrates, and even unicellular organisms (Dember and Richman, 1989). In view of this phylogenetic universality, SAB was designated as "perhaps the most reliable phenomenon in all psychological research"

(Dember and Richman, 1989). Despite its reliability, only limited effort has been undertaken to investigate SAB in humans. Before examining the sparse work done in humans in more detail, the extensive body of animal research on the topic is briefly reviewed.

Research on animals predominantly aimed to identify the mechanisms underlying SAB. Despite the apparent simplicity of the phenomenon, pinning down the relevant cues for alternation has proven most difficult. There are three broad classes of theories accounting for SAB. They assume the critical cue for alternation to be, respectively, the animal's motor response, the stimulus encountered, or the spatial direction taken by the animal.

Postulating the motor response as the basis for alternation was the historically earliest approach in explaining response alternation. Specifically, in a two-alternative forced choice situation, once a motor response is made in one direction, the response in that direction would be inhibited for a certain amount of time. This principle of "reactive inhibition" (Solomon, 1948) has been based on findings in simple T-mazes (Fig. 14a). In T-mazes with a forced 90 degree turn prior to the T-junction, it was shown that invertebrate species alternated directions relative to the orientation of the forced turn (Grosslight and Ticknor, 1953) (Fig. 14b). Analogous to the time course of the recovery phase of a muscle, this behaviour was observed to dissipate when the distance between forced and free choice was increased (Grosslight and Ticknor, 1953) (Fig. 14b).

In opposition to motor response theories, stimulus alternation theories suggest that perceptual factors are driving SAB. Strong support comes from studies using mazes which eliminate an animal's motor response on a first trial but show SAB with respect to the visual properties of the test maze. Dember (1956) had rats entering a T-maze with one arm painted white and the other one black (Fig. 14c). The rat could not enter any of the maze arms, as the entrance was blocked by a glass partition. Visual inspection of the arms was, however, possible. On trial two, the partitions were removed and the colour of one of the arms was changed such that both arms were now either white or black. The rats entered the arm whose brightness had changed. This proves that, even in the absence of any motor response, the mere change in the perceptual characteristics of a maze arm is sufficient to establish a direction preference.

The third class of theories suggests that the spatial direction of a chosen turn is the crucial cue for alternation. Space-based theories of SAB were typically tested with cross mazes as depicted in Fig. 14d. In the first trial, the north side of the cross maze was closed, and the animal entered the maze through the south opening. In the second trial, the closed sides were reversed, and the animal entered the maze through the north opening. This setup allows disentangling response alternation and spatial direction alternation. Results showed that rats alternated the spatial direction, which implied repetition of the previous motor response. Furthermore, forcing rats to take a left-then-right turn in a first maze led to a strong right maze arm preference in a subsequent run through a T-junction (Estes and Schoeffler, 1955) (Fig. 14e) – a result opposite to the one expected on the basis of reactive inhibition of the preceding motor response.

Theories of SAB that rely on concepts of exploratory behaviour, curiosity and novelty seeking are reviewed in (Montgomery, 1952), (Dember and Earl, 1957) and, most comprehensively, in (Richman, Dember and Kim, 1986). These higher-order theories do not necessarily compete with the basic response-, stimulus- or space-based accounts summarized above. Quite possibly, no single theoretical account of SAB has to be favoured over others, as the manifestation of choice alternation outside the laboratory and the potentially adaptive value of the phenomenon may vary considerably across species (Harvey and Bovell, 2006). Framing the problem of alternation in more general terms than the reliance on visual stimulus, motor response or spatial direction may be especially important for the understanding of SAB in humans – a topic to which we turn in the following paragraph.

The extensive work done in animals has ever been in striking contrast to the surprisingly low number of SAB studies in humans, despite multiple implications for psychological research (Schultz, 1964). Up to this point, examinations of SAB tendencies in humans have not managed to move beyond a superficial inspection of the phenomena, solely addressing the question: “Do they or don’t they?” (Richman, Dember and Kim, 1986). Pate and Bell (1971) had preschoolers crawl twice through a maze constructed out of opaque playground tunnels. They described alternation rates of more than 80%, generally increasing with a child’s age. To our knowledge, the only study on adult human subjects’ SAB in a maze-like situation is by Neiberg, Dale and Grainger (1970). These authors recorded college students’ directional choices while they repeatedly walked through a T-shaped corridor. They found an alternation rate of 60%, not significantly different from the chance rate of 50%.

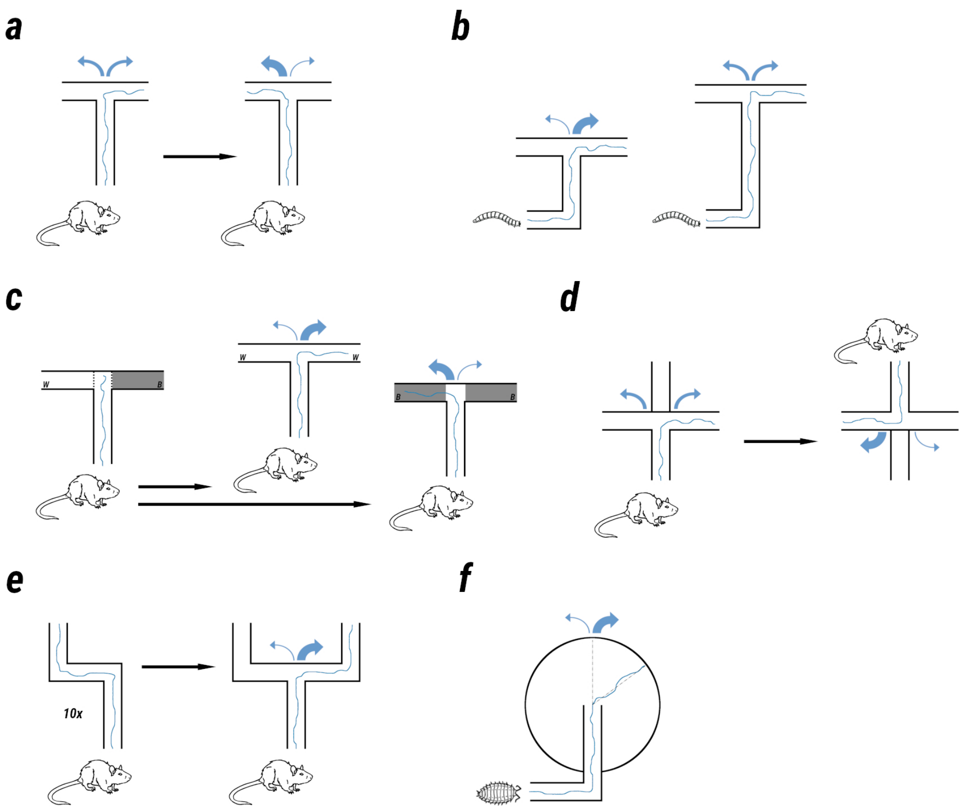


Fig. 14: Schematic depiction of maze designs used in studies of SAB in animals. Thin black arrows represent two consecutive trials. The strength of directional preferences at free choice junctions is represented by the thickness of light blue arrows. Sample trajectories through the mazes are indicated. See text for explanation and references.(a)-(b) depict findings supporting response theories of SAB: (a) Classical setup used in the examination of SAB in rodents. During two consecutive trials in a T-maze, in the second trial the direction opposite to the initially chosen direction is preferred. (b) T-mazes used to demonstrate turn alternation at the free choice junction after a 90-degree forced turn, which is diminished by prolongation of the distance between forced and free turn. (c) shows a setup used to support stimulus theories of SAB: A first exposure to a T-maze with a black and a white painted arm after the T-junction allows only visual experience (without motor response) of the corridors due to a glass partition. In subsequent trials the rat shows “stimulus alternation”, i.e. a preference for the goal arm, whose colour had been changed. (d)-(e) illustrate findings in support of spatial direction alternation in SAB: (d) shows the use of a cross maze to disentangle response cues and spatial direction cues. After entering a T-maze from one side and choosing a direction at the T-junction, subsequently entering the T-maze from the opposite side leads to a preference of the goal arm pointing in the spatial direction opposite to the one initially chosen, thus involving a repetition of the motor response. (e) Tenfold exposure to a forced left-right turn sequence leading to a right turn preference at a subsequent T-junction. (f) shows the angular deviation from a straight-ahead direction pointing opposite to the direction of a preceding 90 degree forced turn.

Given the impracticality of building life-size mazes for humans, some researchers have studied maze exploration outside the context of walking, requiring subjects to trace mazes drawn on paper (Ellis and Arnoult, 1965; Harris, 1971) or guide a hand-held stylus along small 3D maze models (Lawless and Engstrand, 1960). All these studies, mostly testing young children, reported significant alternation behaviour. However, the significance of human alternation behaviour extends far beyond issues of directional choices in a maze. Above-chance alternation was also found in more abstract types of "exploration" behaviour, e.g. in unreinforced binary guesses of the alternatives "LEFT" and "RIGHT" (Iwahara and Suginiura, 1969), in repeated free choices between objects (Jeffrey and Cohen, 1965; Miller *et al.*, 1969; Vecera, Rothbart and Posner, 1991) or among verbal response options (Croll, 1966). Even more broadly, cognitive biases like the "gambler's fallacy" in Roulette (Tune, 1964) and the "hot hand" in basketball (Gilovich, Vallone and Tversky, 1985) are further illustrations of the pervasiveness of alternation behaviour.

The fact that alternation of choices is favoured over repetitions in these contexts led us to suggest that paradigms of SAB are conceptually equivalent to paradigms which require human participants to generate random sequences of alternatives (Brugger, 1997). In both contexts the avoidance of generating an identical response on consecutive trials is the most prominent bias. However, the purported conceptual equivalence between spontaneous maze alternation and repetition avoidance in subjective randomization has never been empirically tested. Such equivalence would suggest that "movements" in abstract spaces (search in memory, establishing connections in social networks) obey the same laws as locomotion in maze exploration. In addition, it would indicate that SAB in sequential decision making might reflect the primacy of exploration over exploitation in the healthy brain (Hills *et al.*, 2015), which could make SAB tests candidate instruments to detect both highly functioning cognitive traits (de Manzano and Ullén, 2012) but also to uncover early signs of cognitive decline (Gauvrit *et al.*, 2017).

The lack of classic, locomotion-based SAB experiments in humans may in part be due to the difficulties posed by the use of walkable mazes. Apart from the effort of building a life-size maze, the appearance and properties of the different corridors should either be identical or changeable in a systematic way. Recent advances in virtual reality (VR) technology offer a solution to these problems. Using position tracking combined with head mounted displays (HMDs), one can easily build immersive virtual mazes, through which a user can navigate by real walking. By this approach, the features of the maze's appearance, such as structure, texture, brightness and surroundings, can be precisely controlled for. The advantages of virtual mazes have long been recognized by behavioural neuroscientists (Tarr and Warren, 2002). Using virtual realizations of the eight-arm radial maze and the Morris water maze, spatial memory was tested in humans using paradigms normally restricted to animal subjects (Cornwell *et al.*, 2008; Spieker *et al.*, 2012). Furthermore, studies investigating the use of virtual mazes in animal experiments underline the feasibility of translating spatial tasks from the real world to virtual reality (G. Chen *et al.*, 2018). Expanding this approach to the study of alternation behaviour, we recently used a virtual maze to demonstrate SAB in walking adults (Nguyen *et al.*, 2017). Overall, participants significantly alternated turn directions with a rate of 72%, thus providing first evidence for directional above-chance alternation in adults' locomotion.

It is not clear whether the lack of an overarching theory of SAB or the increasing use of SAB paradigms for applied purposes (especially in pharmaceutical contexts (Hughes, 2004)) has slowed down basic research in the field. In any case, contributions to the very nature of "perhaps the most reliable phenomenon in all psychological research" (Dember and Richman, 1989) have undoubtedly become relatively sparse compared to the period between 1940 and the 1970ies. The series of experiments proposed here aims at picking up the thread and initiate the systematic investigation of human SAB. By bringing the traditional paradigm of SAB to the VR lab, studying the effects of cognitive load on alternation rates (Experiment 1), and adding novel techniques to examine "alternation" in human participants (Experiment 2 and 3), we hope to spark the interest of those scientists studying human behaviour, who are still keen to maintain an across-species comparative perspective.

12.1.1 Experiment 1: SAB under cognitive load and its relation to random number generation

Alternation at a junction is dependent on the choice in the previous trial and gives thus testimony to the fact that this choice is somehow remembered (physiologically or cognitively). Even though there have been observations that bilateral hippocampal lesions abolish SAB in rats (Kirkby, Stein and Kimble, 1967; Dalland, 1970), and that dual-task paradigms diminish repetition avoidance in humans attempting to generate random numbers

(Brugger, 1997), the role of memory in human SAB has never been empirically investigated. Theories suggesting a central role of memory in SAB (Lalonde, 2002) would predict alternation rates to decrease under added cognitive load because of its detrimental effect on remembering the previous turn.

We proposed to investigate the effect of cognitive load on SAB in the virtual maze used in (Nguyen *et al.*, 2017) (the “triple T-maze” henceforth; see Fig. 15b). This maze design offers an ideal setup to estimate conventional alternation rates in a quick fashion. Assuming that memory is an integral component of human SAB, we hypothesized that an increase in cognitive load leads to reduced alternation rates. As a dual-task we used an auditory Stroop task, in which the participants (while walking) repeatedly heard the words “Frau”/”woman” and “Mann”/”man” spoken by either a woman or a man (Green and Barber, 1981). Thus, voice and word were either congruent or incongruent. Participants had to indicate the gender of the speaker for each presentation. Before the virtual maze experiment, we additionally assessed repetition avoidance in a Mental Dice Task (Geisseler *et al.*, 2016). The Mental Dice Task is a random number generation task that requires the paced naming of the digits from 1 to 6 in a sequence mimicking consecutive rolls of a fair dice as closely as possible. The assessment of repetition behaviour with the Mental Dice Task allowed us to test the notion of a conceptual equivalence of response alternation in random number generation and SAB in maze exploration (Brugger, 1997). This was more than just a superficial correlation analysis; any association between the avoidance of repetition on a highly cognitive level (Brugger, Landis and Regard, 1990) and that on the level of effector physiology (Brugger, Macas and Ihlemann, 2002) might point to some fundamentals in the control of the serial order of behaviour (Lashley, 1951).

12.1.2 Experiment 2: Disentangling locomotor and visual factors contributing to human SAB

As described above, a wealth of animal studies has compared the influence of motor responses as vital cues for alternation with the influence of other factors, especially visual cues. Studies on human alternation behaviour have never considered this distinction. In the second experiment, we aimed at expanding this type of investigation to human SAB. We did so by investigating the relative effects of the physical and visual perception of a forced turn on alternation rates.

The VR setting seems ideally suited to disentangle the contributions of locomotion and vision to human SAB. In virtual environments presented via HMDs, a user's physical actions often do not correspond to the visually perceived movements. For example, a user might be sitting on a chair, while navigating through a virtual environment on the screen. This discrepancy between visual and bodily perception plays a major role in the development of VR applications and is at the heart of many yet unsolved issues in VR such as optimal immersion (Usoh *et al.*, 1999) or simulator sickness (Kolasinski, 1995). Although it is technically straight-forward to translate real life movements one-to-one to the virtual world by the use of body tracking, this is often problematic due to space restrictions in the physical world. The method of redirected walking is a software-based approach to this problem: By manipulating the way physical movements are mapped on the virtual space, a user's walking trajectory can be shortened or bent, allowing the exploration of virtual environments much larger than the available physical space (Razzaque, Kohn and Whitton, 2001; Hodgson and Bachmann, 2013).

We proposed to adopt the method of redirected walking to investigate the relative contributions of physical and visual perception to SAB in human walkers. One key procedure of redirected walking, the curvature gain, inserts a slight rotation of the virtual scenery around a user when he or she is moving, causing the user to walk on a curved pathway in order to correct for the inserted rotation. By combining curvature gains with curved or straight T-mazes, we can make a participant experience a forced turn prior to a T-junction only physically ("physical" condition), only visually ("visual" condition) or both visually and physically ("congruent" condition) (see Fig. 15c).

It must be noted, that this investigation differs slightly from conventional SAB paradigms, which were used to investigate the physical and visual cues for alternation in animals. Especially regarding the visual cues, SAB studies have classically focused on the visual appearance of maze arms. By manipulating the visual characteristics of the two goal arms in a T-junction, the influence of visual cues on alternation behaviour could be assessed (Walker *et al.*, 1955). In the here proposed experiment, however, we do not test the influence of the visual appearance of maze arms on alternation rates, but rather whether visually (or physically) perceiving a turn triggers a subsequent alternation response. Thus, the described setup allows estimating the relative effects of a forced turn's physical and visual component on the subsequent alternation rate in a T-junction.

Preliminary results suggested that the physical component of the forced turn is detrimental to alternation rates in humans, possibly because of the additional effort to change the current turning direction of the curved pathway prior to the T-junction (see section “Pilot data and power analysis”, page 110). On the other hand, we expected the visual representation of the forced turn to be positively driving turn alternation, an expectation that is partly based on previous studies, which emphasize the predominant visual component of animals’ and specifically primates’ SAB (Dember, 1956; Izumi, Tsuchida and Yamaguchi, 2013). Therefore, we hypothesized an increased alternation rate in the visual condition relative to the congruent condition and a decreased alternation rate in the physical condition relative to the congruent condition. Further, we hypothesized that participants show significant alternation in the congruent condition.

12.1.3 Experiment 3: Moving beyond binominal data by walking into an open space

In the third experiment, we planned to investigate the existence of SAB beyond its classic, corridor-based framework. Examining SAB in other types of maze architectures presents a crucial step in understanding SAB’s generalizability and flexibility in human walking. While it has been shown that humans exhibit SAB in bifurcation mazes, whether human SAB extends further outside that framework has never been tested. In insects, isopods and myriapods, SAB has been observed in a modified paradigm where the animals deviate from a straight locomotor path at the exit of a maze. This deviation points opposite to the direction of the previously traversed forced turn (Fig. 14f) (Barnwell, 1965). In this paradigm, SAB is not expressed as a binomial variable (“alternation” or “repetition”) but as a continuous variable (the angle of deviation from the straight locomotor path, also dubbed the “reverse turning” angle (Schäfer, 1982)). Like the dichotomous measure of SAB, this angle decreases with increasing walking distance between forced turn and the maze exit (Hughes, 2008). Using a continuous variable as a measure of SAB is statistically more powerful (Czaczkes, 2018) and could therefore allow identifying smaller effect-sizes.

We proposed to implement this modified SAB paradigm for human walkers using virtual reality. The maze, modelled after mazes used in lower arthropods, consisted of an initial 90 degree forced turn that leads into an open area (the “open maze”, henceforth; see Fig. 15d).

On the basis of work in arthropods (Barnwell, 1965) we hypothesized reverse turning to occur also in human participants.

12.2 Material and methods

12.2.1 Participants

288 healthy, right-handed participants, within the age range of 18-40 years, were tested. Handedness was assessed with a shortened version of the Edinburgh Handedness Inventory (Veale, 2014). Gender of the participants was balanced. Exclusion criteria included any history of neurological, vestibular or psychiatric disorder. Any injuries affecting the natural gait of participants also led to non-inclusion in the study. Participants were informed about the exclusion criteria beforehand and asked to only apply if no criteria are violated. Participants were mainly recruited using the online forum “Marktplatz” of the University of Zurich (UZH) and via mailing lists of the psychology department of the UZH. Reimbursement for participation was 10 Swiss francs (the approximate duration of the study was 20 minutes). Participants were asked to sign an informed consent form prior to starting the experiment. All experimental procedures had been approved by the Cantonal Ethics Committee of Zurich and were carried out in accordance with the ethical standards of the Declaration of Helsinki.

12.2.2 Experimental procedures

12.2.2.1 General procedure

The study consisted of three experiments, each including a specific type of virtual maze. Each participant took part in all three experiments. Experiment 1 consisted of two walks through the “triple T-maze”, experiment 2 consisted of three walks through the “curved T-maze” and experiment 3 consisted of one walk through the “open maze”, resulting in 6 walks per participant (see Fig. 15). To counteract possible order effects between trials, the order of the six walks was randomized and balanced across participants. One constraint in the randomization was that two trials of the same experiment are never conducted right after each other (see page 153 for a full description of the randomization scheme).

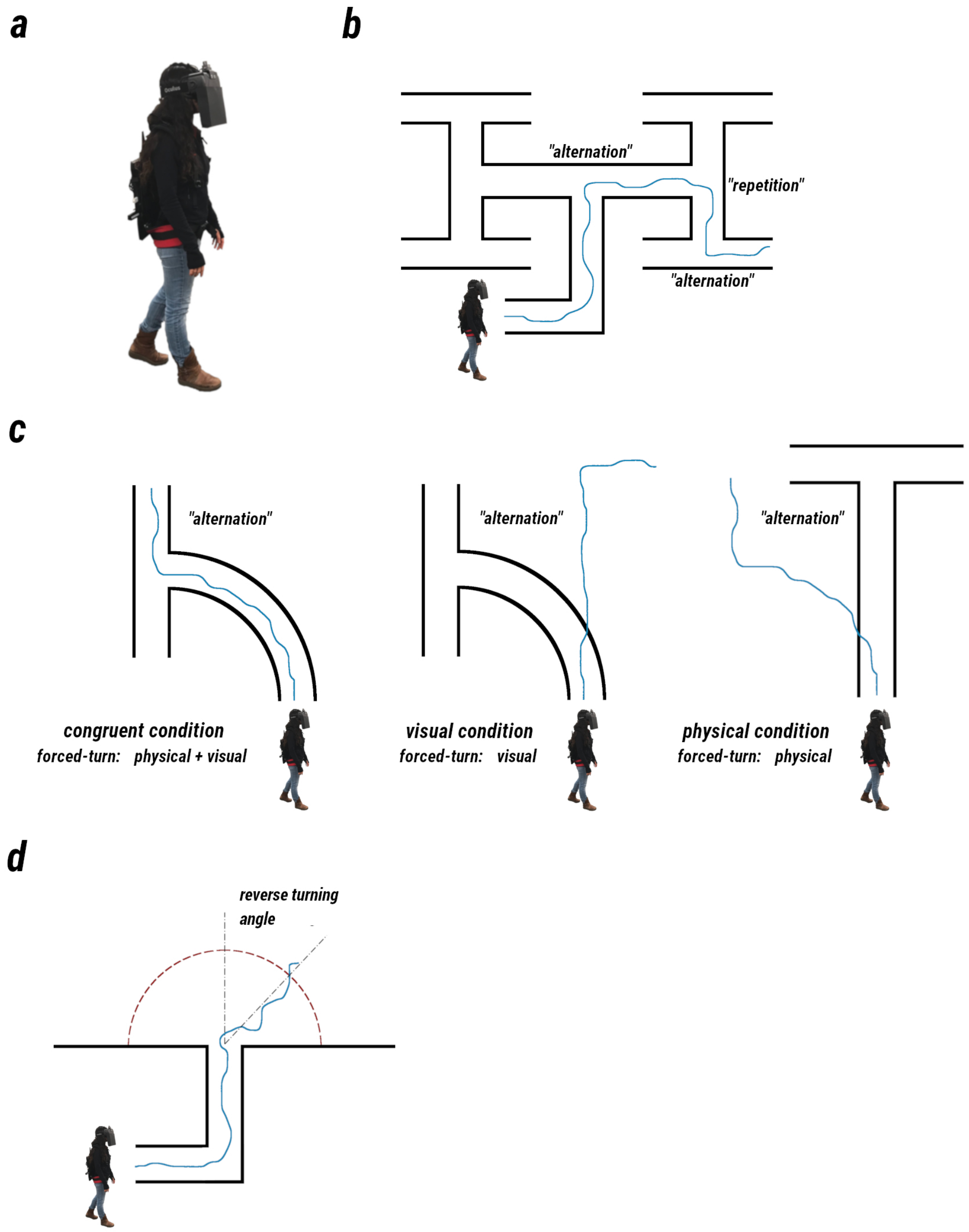


Fig. 15: Depiction of a participant and schematic drawings of the virtual mazes. (a) Participant wearing an Oculus DK2 and a laptop running the VR simulation on the back. The HMD is equipped with a visual cover to prevent visual feedback from the ground. (b) The triple T-maze of experiment 1. Scored responses are indicated at the three T-junctions. (c) The three curved T-mazes of experiment 2. The blue lines represent the physical trajectories, which are not congruent with the maze outlines due to the applied redirected walking (curvature gain) in the "visual" and "physical" conditions. (d) The open maze of experiment 3. The reverse turning angle is indicated for a fictional walking pathway (blue line) at a specified distance from the corridor exit.

Participants wore an Oculus DK2 HMD with an Intersense IS-1200 optical tracking system mounted on top for 6 DOF head position tracking at 180 Hz (Foxlin and Naimark, 2003) in a 12 m x 6 m tracking area. The virtual maze environments were generated in Unity, which ran on a laptop carried by participants on their back during the experiment (Fig. 15a). This setup allowed participants to wander freely, without being tethered to a stationary computer. Before each walk through the maze, a starting position and orientation was shown through the HMD and the trial started once the participants had reached the indicated starting position and orientation. The procedure was fully automated and did not require the involvement of the experimenter. The experimenter viewed the same virtual scene as the participants through a separate display and only interfered when technical problems arose.

Participants were not informed about the actual focus of the study and were only instructed that they will be exposed to maze-like virtual environments, in which they are invited to freely move around. The only limitations to their exploration were 1) participants should not turn around (180 degree turn) when walking in a corridor and 2) when coming across open spaces, participants can walk around in theses spaces but not go back into the corridor they came from. After completing all trials, participants were asked whether they have followed a specific strategy to navigate through the VEs and, if yes, to characterize this strategy. The answers to this question were considered for a potential explorative analysis, examining differences between individuals, who adhered to specific navigation strategies, and participants walking without strategy.

12.2.2.2 General pre-processing and statistical procedures

Based on the head tracking recordings, the walking trajectories throughout the mazes were calculated for each participant. There was no outlier removal in the collected data. If at any point technical issues arose during an experiment interfering with the experiment’s procedure or data-logging, the participant was excluded from the experiment, in which the issue emerged, and replaced by a new participant. Issues rated as interfering with the experiment’s procedure included any type of freezing of the displayed virtual environment or any other faulty distortion of the presented virtual environment. Technical issues were recognized by the experimenter, who monitored the procedure of all experiments on a separate display. In case of a participant wanting to stop the experiment due to motion sickness or any other discomfort, he/she was excluded from all experiments independent of how many trials had already been completed.

All statistical analyses were performed with the statistics software R, using a significance level of $\alpha = 0.02$. For each tested value, the associated 98% confidence interval is reported. Analyses involving mixed-effects models were performed with the R packages "lme4" and "lmerTest" (R Development Core Team, 2008; Bates *et al.*, 2015). Confidence intervals for coefficients in mixed-effects models were based on parametric bootstrapping. Mixed model formulas in the following sections are given in the notation style of the lme4 package.

12.2.2.3 Experiment 1

Procedure

The maze of experiment 1 consisted of an initial 90 degree forced turn, followed by three consecutive T-junctions (see Fig. 15b). The distances between turns consisted of 2.5 m long corridors with a width of 1 m. Participants performed two walks through the maze, once with and once without performing a dual-task. The direction of the initial forced turn was randomized and counterbalanced over participants. The dual-task consisted of the auditory Stroop task (Green and Barber, 1981). In this task, participants were presented with audio playbacks of the words "Frau"/"woman" and "Mann"/"man" spoken by either a woman or a man (German terms were be presented to German-speaking participants, English terms to English-speaking participants). The stimuli were recorded from computer-generated male and female voices, using three different artificial voices for each gender. Participants were asked to verbally report the gender of the speaker. Starting with the first step into the maze, new audio playbacks were presented in time intervals of two seconds. Participants were instructed to react as fast and accurately as possible. Correctness of the responses were scored, but we did not intend to analyse this variable any further, as the main purpose of this task was to introduce cognitive load. In the control condition, participants walked through the maze without hearing any audio playbacks.

The auditory Stroop task was chosen because of the task's lack of a spatial component. More conventional dual-tasks, such as for example the serial-7 or serial-3 subtraction tasks, are known for their potential to introduce a spatial bias in the participant, due to the internal representation of numbers on a mental number line (expanding from left to right; (Loetscher and Brugger, 2007)). Such implicit spatial bias could interfere with the alternation of turn directions in the maze. In addition to the absence of a spatial bias, the auditory Stroop task has been shown to reliably engage walking humans' working memory (Plummer-D'Amato *et al.*, 2012).

Prior to the experiment, participants completed a training session to familiarize themselves with the concurrent task. While sitting, they were presented with five audio playbacks of the auditory Stroop task, to which they had to verbally react appropriately. Participants were informed that at one point during the experiment, they would have to react to audio playbacks in the fashion just trained. In addition, participants performed a Mental Dice Task while sitting, without being immersed in a virtual environment. In the Mental Dice Task, participants were asked to generate a random number sequence with digits ranging from 1-6, mimicking the rolls of a fair dice. In total, 66 numbers were generated with a 1Hz frequency. The timely generation of new numbers was dictated by a metronome. The random number sequences were recorded following the procedure described in (Geisseler *et al.*, 2016).

Analysis pipeline

The three junctions of the maze were scored as a repetition or alternation in relation to the chosen turn direction in the immediately preceding turn (see Fig. 15b). The direction decision at the first junction was evaluated in relation to the direction of the initial forced turn. We hypothesized that participants would significantly alternate direction choices in the control condition and that in the dual-task condition this alternation rate would be decreased. To test these hypotheses, an overall alternation rate was calculated for the control condition. This was achieved by fitting a mixed-effects logistic regression model to the alternation responses of the participants in the control condition, only including participants as a random intercept (alternation ~ (1|participants)). The intercept of this fit was tested against a value of zero, which is identical to testing the overall alternation rate against an alternation rate of 50% (the estimated intercept of the logistic regression is equal to log(P(alternation) / (1-P(alternation))), therefore an intercept of zero corresponds to an alternation rate of 0.5, since log(0.5/0.5) = 0). This analysis additionally served as a replication of our previous study, in which a significant overall alternation rate of 72% was observed (Nguyen *et al.*, 2017). Subsequently, a mixed-effects logistic regression model was fitted to the entire data, including alternation responses as the target variable, condition (two-level factor, with/without dual-task) as a predictor and participants as a random intercept (alternation ~

condition + (1|participants)). The coefficient of the condition factor was tested against a value of zero.

To test the hypothesis of a conceptual equivalence between alternation behaviour in walking and repetition avoidance in random number generation, the amount of participants' digit-repetitions in the Mental Dice Task was correlated (Pearson correlation coefficient, two-sided) with the reverse turning angles measured in experiment 3. As positive values of this latter measure reflect a higher alternation tendency, we predicted the correlation to be negative.

Power analysis

The assumed parameters used for the power analysis were taken from (Nguyen *et al.*, 2017). The respective study revealed an overall significant alternation rate of 72% in the control condition in a sample size of 49 participants. The random effect of participants was estimated to entail a standard deviation of 5×10^{-8}. A power analysis, incorporating this random effect and an assumed alternation rate of 72%, revealed a necessary sample size of 28 participants to detect an alternation rate in the control condition different from chance with a power of 90%.

An additional power analysis was performed to investigate the sample size necessary to detect a difference of alternation rates between the two conditions (with/without dual-task). Because there are no data on the effect of a dual-task on alternation rates in walking humans, it is reasonable to rely on dual-tasks experiments from general alternation experiments to estimate expected effect sizes. However, despite a variety of dual-task experiments in random number generation, the translation of effects to SAB rates is difficult to achieve. In random number generation the randomness of the produced sequence, which consists of more than just two possible elements (usually the numbers 1-9), is scored as a mathematical index or an entropy value, which does not correspond directly to an alternation rate. What remains is to fall back to animal experiments. Although in the animal literature on SAB classical dual-task paradigms have not been employed, there are studies in which visual cues from a maze were gradually removed, making it more difficult for the animal to remember them in upcoming trials. Gerbils alternated in a standard T-maze with a rate of 72% (Dember and Kleinman, 1973), an alternation rate comparable to the one found in humans walking through a virtual maze (Nguyen *et al.*, 2017). When removing internal cues from the maze, leaving only spatial orientation, alternation rates of gerbils dropped to

55%. Removing all possible cues from a maze resulted in an alternation rate of 50% (Dember and Kleinman, 1973). Based on these results we concluded that a decrease in alternation of 15% is a reasonable estimate of the dual-task effect on human alternation rates. Using this decrease as the assumed effect size results in an alternation rate of 57% in the dual-task condition. The power analysis revealed a necessary sample size of 135 to detect the assumed alternation decrease with a power of 90%.

For the correlation test between the participants' number of digit-repetitions (Mental Dice Task) and the reverse turning angles, the power analysis (assuming a medium effect of correlation between the two variables of 0.3 (Cohen, 1977)) indicated a needed sample size of 139 to reach a power of 90%.

12.2.2.4 Experiment 2

Procedure

The second experiment consisted of one walk through each of the three curved T-mazes (Fig. 15c). Using redirected walking (curvature gain), the participants' walking trajectories were manipulated while walking through the T-mazes in the physical and visual condition. In the physical condition, a curvature gain of 0.25 (curvature gain = 1/(radius of curvature)) was applied to force participants onto a curved walking trajectory while passing through the visually straight passage leading up to the T-junction. The gain intensity of 0.25 lies above the detection thresholds for curvature gains reported in the literature (Steinicke *et al.*, 2010; Neth *et al.*, 2012; Grechkin *et al.*, 2016; Rothacher *et al.*, 2018). Thus, the curved walking was expected to be physically perceived as such by the participants. The curvature gain was applied until participants had reached the T-junction. In the visual condition, a curvature gain of the same intensity was applied in the opposite direction of the curved turn to force participants into a straight walking trajectory while passing through the visually curved corridor leading up to the T-junction. In the congruent condition, no curvature gain was applied, which lead to participants walking the curved turn congruent with their visual experience of the maze. The mazes and applied curvature gains were designed in a way that the radius (4 m) and length (6.28 m) of the walked or visually perceived curvatures were equal in the physical, visual and congruent condition. The width of the corridors in the curved T-mazes was 1.5 m. Participants were not informed about the redirection before the experiment. The directions of the forced turns (left/right) were randomized and counterbalanced over participants for each T-maze.

Analysis pipeline

The chosen directions in the T-mazes were scored as alternations or repetitions in relation to the direction of the preceding curved turn. We hypothesized that participants show significant alternation in the congruent condition. Furthermore, we hypothesized that compared to the congruent condition, alternation rates would decrease in the physical condition while the visual condition would lead to an increase in alternation rates. To test these hypotheses, in a first step the alternation behaviour of all participants in the congruent condition was tested against an alternation rate of 50% using a one-sided binomial test. To compare this alternation rate with the two other conditions, a mixed-effects logistic regression model was fitted using alternation behaviour as the target variable, condition (three level factor, physical/visual/congruent) as a predictor, and participants as a random intercept (alternation ~ condition + (1|participants)). Using the congruent condition as the reference, the differences to the other two conditions are expressed by the two respective condition-factor coefficients, which were tested against a value of zero.

Pilot data and power analysis

To determine the expected effect sizes for the power analysis, the alternation rate in the congruent condition had to be estimated first. The most closely comparable data to alternation behaviour in a curved T-maze are from (Nguyen *et al.*, 2017), in which participants showed an alternation rate of 76% in response to the primary forced turn. However, a sharp 90 degree turn as in (Nguyen *et al.*, 2017) might differ from a smooth, curved 90 degree turn in terms of the elicited alternation response. To get a more appropriate estimate of the alternation rate, a pilot study was conducted including 60 participants, who walked through the curved T-maze in the congruent condition. The results of the pilot study indicated an alternation rate in the curved maze of only 60% (one-sided binomial test: $p = 0.0775$). A power analysis for a one-sided binomial test (based on the discrete binomial distribution) revealed a necessary sample size of 282 participants to distinguish the assumed alternation rate of 60% from chance with a power of 90%.

To estimate the difference between alternation rates in the congruent and the physical condition, a further pilot study was conducted. 30 participants completed the T-maze in the physical condition (using a curvature gain of 0.2). The participants showed an alternation rate of 40% (95% CI: 0.23 - 0.59). Regarding alternation behaviour in the visual condition, there is no pilot data available, and no previous study has investigated comparable effects in humans. Analogous to the estimation of the effect of a dual-task in experiment 1, we decided an increase of 15% to be a reasonable effect size estimation. Such an increase would assume an alternation rate of 75% in the visual condition. A power analysis, incorporating the assumed alternation rates in the three conditions (visual, physical, congruent) and the random effect of participants taken from (Nguyen *et al.*, 2017) (see section “Power analysis”, page 108), revealed a necessary sample size of 170 participants to distinguish a difference between the congruent condition and the physical condition with a power of 90%. For the distinction of the alternation behaviour between the congruent and the visual condition, a sample size of 265 was revealed to be necessary.

12.2.2.5 Experiment 3

Procedure

Participants found themselves in a 1 m meter wide corridor at the beginning of the open maze experiment (Fig. 15d). First, participants passed through a 2.5 m long corridor to reach the initial 90 degree forced turn. The direction of the forced turn (left/right) was counterbalanced among participants in a randomized order, leading to half of the 288 participants completing the open maze with an initial forced right turn, while the other half completed the open maze with an initial forced left turn. Subsequently, participants walked a 4.5 m long corridor leading into an open space. The open space was only limited by walls running perpendicular to the corridor walls, blocking the participants to walk behind the level of the corridor exit. Apart from these walls, the open space was empty and seemingly infinite, showing only the horizon when looking forward into the open space. Participants were free to walk in any direction desired, except for walking back into the corridor (as instructed before the experiment). Participants were stopped as soon as they had passed a distance of three meters from the corridor exit. In the case of a participant stopping in the open space, asking where he/she is supposed to go, the experimenter instructed the participant to “just walk a bit further wherever you want to go”.

Analysis pipeline

The outcome variable of experiment 3 was the reverse turning angle, which expresses the deviation in the open space relative to the direction of the prior forced turn (Fig. 15d). Positive angles denote directions opposite to the forced turn direction and therefore an alternation, while negative angles denote a repetition of direction in the open space. To test our hypothesis that participants generally alternate their chosen direction in the open space, we tested the mean of all reverse turning angles in a one-sample t-test against a value of zero in a one-sided fashion. In the case of reverse turning angles not following a normal distribution (tested by Kolmogorow-Smirnow test and inspection of the normal qq-plot), a one-sample Wilcoxon signed rank test would be applied as a non-parametric alternative to the one-sample t-test.

Pilot data and power analysis

Since no prior experiment has tested a similar paradigm in humans, a pilot study was performed to test the experiment's feasibility and to estimate the expected effect size. 30 healthy participants were sent through a virtual open maze, counterbalanced for left- and right-directed initial forced turns. Procedure and data collection were identical to the here proposed procedure. In the pilot study, the reverse turning angles showed a sample standard deviation of 26.2 degrees and a mean value of 7.6 degrees (one-sided t-test: $t = 2.23$, $p = 0.0147$). Assuming these results to represent the true parameters, a power analysis revealed a necessary sample size of 137 participants to detect a mean reverse turning angle greater than zero with a power of 90% using a one-sided t-test.

12.2.2.6 Timeline

Due to the large sample size, we estimated a duration of four months for the recruitment and testing of all participants. After data collection, we estimated the analysis and the final writing of the manuscript to maximally take another two months. Therefore, the study was anticipated to be completed in six months total.

12.3 Results

12.3.1 Experiment 1

12.3.1.1 Planned analyses

In the triple T-maze participants showed an overall alternation rate of 60.4% in the control condition, significantly higher than the chance rate of 50% ($p = 1.21*10^{-9}$, 98%-CI: [56.6%, 64.3%]). In the dual-task condition the alternation rate dropped to 55.8%, this decrease from the control condition, however, was non-significant (b = -0.19, p = 0.051, 98%-CI: [-0.418, 0.038]). Participants' alternation tendencies in the triple T-maze are visualized in Fig. 16.

Participant's digit repetitions in the Mental Dice Task were not significantly correlated with the reverse turning angles measured in experiment 3 (r = 0.074, p = 0.211, 98%-CI: [-0.064, 0.209], see Fig. 17).

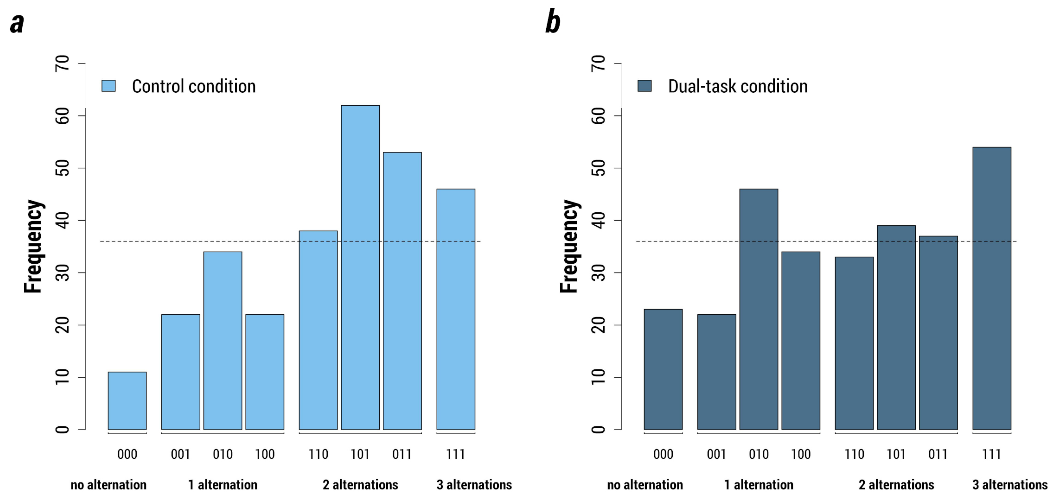


Fig. 16: Histograms of the different alternation patterns exhibited in the triple T-maze. The three traversed T-junctions are scored as 0 for repetition of direction and as 1 for alternation. The eight possible pathways range from no alternation at all (000) to the maximum of three alternations (111). The frequencies for the possible trajectories are shown for the control condition (a) and the dual-task condition (b).

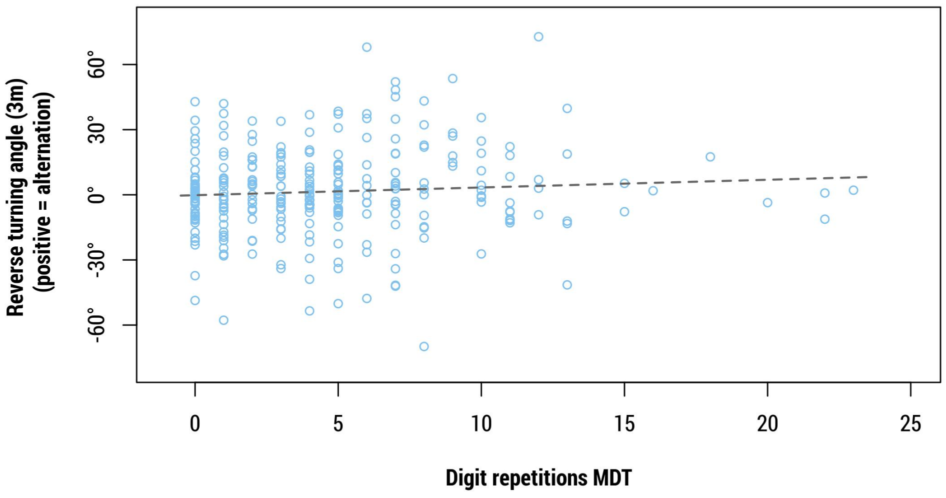


Fig. 17: Scatter-plot of digit repetitions in the Mental Dice Task versus the reverse turning angles of experiment 3 at three meters from the corridor exit. The regression line (dotted) is shown in grey.

12.3.1.2 Exploratory analyses

The alternation rate of 55.8% in the dual-task condition was significantly higher than the chance rate of 50% ($p = 0.0007$, 98%-CI: [52.5%, 59.1%]). There was no significant left- or right turn preference in participants (right turning rate of 48.1%, $p = 0.112$). There was no significant gender effect in alternation behaviour ($b_{gen}(m) = -0.019$, $p = 0.845$) nor in side preference ($b_{gen}(m) = -0.125$, $p = 0.194$). In the junction immediately after the initial forced turn in the triple T-maze, participants alternated with a significant rate of 58.3% in the control condition ($p = 0.006$, 98%-CI: [51.3%, 65.1%]). In the control condition, after turning two times in the same direction (left-left or right-right) participants alternated the direction at the subsequent junction with a significant rate of 73% ($p = 3.34*10^{-11}$, 98%-CI: [65.2%, 80.0%]). Participants' digit repetitions of the Mental Dice Task did not significantly correlate with the individual alternation tendency in the triple T-maze ($r = -0.093$, $p = 0.117$).

12.3.2 Experiment 2

12.3.2.1 Planned analyses

In the congruent condition participants alternated with a rate of 61%, which was significantly higher than 50% (p = 0.0002, (one-sided) 98%-CI: [54.6%, 100%]). In the subsequent mixed-effects logistic regression analysis, the visual and physical condition showed an identical decrease in alternation compared to the congruent condition, but in both cases the decrease remained non-significant (b_{vis} = -0.203, p = 0.234, 98%-CI: [-0.603, 0.184]; b_{phy} = -0.203, p = 0.234, 98%-CI: [-0.608, 0.190]).

12.3.2.2 Exploratory analyses

In both the visual and physical condition participants alternated with a rate of 55.9%, which was not significantly different from chance (p = 0.052, 98%-CI: [48.9%, 62.8%]). Participants did not show a significant left- or right turn bias (right turning rate of 52%, p = 0.248). There was no significant gender effect in alternation behaviour (b_{gen}(m) = 0.067, p = 0.634) nor in side preference (b_{gen}(m) = 0.064, p = 0.634).

12.3.3 Experiment 3

12.3.3.1 Planned analyses

The mean reverse turning angle was 1.46 degrees (SD = 20.2 degrees), not significantly larger than zero (t = 1.23, p = 0.11, (one-sided) 98%-CI: [-0.99, Inf]).

12.3.3.2 Exploratory analyses

Participants did not show a general left- or right turn bias (mean right-turning angle 1.76 degrees, p = 0.139). There was no significant gender difference in alternation behaviour (t = 1.37, p = 0.171) nor in side preferences (t = 1.078, p = 0.282). In Fig. 18 mean reverse turning angles are plotted against the distance in the open space from the corridor exit.

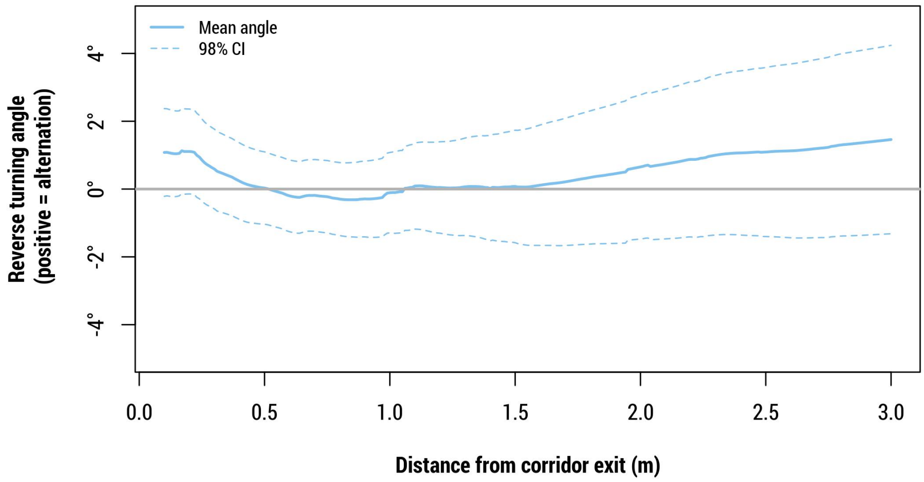


Fig. 18: The mean reverse turning angle is plotted against the distance from the corridor exit in the open maze. The 98% confidence interval is represented by dashed lines.

12.4 Discussion

In the current study, we aimed at investigating the presence of SAB in walking human adults. To this end, we performed three experiments on a sample of 288 healthy participants. In each experiment, participants were asked to explore a specific type of virtual maze. The most conventional estimation of alternation rates was performed in the first experiment. In the first experiment, participants traversed through the triple T-maze, which is a concatenation of three consecutive T-junctions (Fig. 15b). In the triple T-maze participants showed an overall significant tendency to alternate direction choices with a rate of 60.4%. Although this is evidence for the presence of SAB in walking humans, the found alternation rate was smaller than expected. In a previous study (with a sample size of 60 participants), an overall alternation rate of 72% was found using the same virtual maze (Nguyen *et al.*, 2017). These two experiments have used a very similar population to draw participants from and the instructions to participants were identical. Therefore, it is difficult to explain the observed drop in alternation. Given the much larger sample size of the current study, however, the results presented here possibly provide a more precise estimate of alternation rates representative of human subject populations. The trend towards alternating directions when choosing a pathway through the triple T-maze can also be recognized in Fig. 16a (and to a lesser degree in Fig. 16b). One potentially noteworthy observation in Fig. 16 are the relative peaks of the pathways 010 and 101. The pathways include one and two alternations respectively. The question arises whether the peaks are a trace of a kind of meta alternation, i.e. a repetition avoidance of alternation itself. In a previous study on SAB the same peaks were observed for the two pathways (Nguyen *et al.*, 2017). The possibility of such higher-level alternation patterns should be considered in the design and analysis of future SAB studies.

The dual-task condition of experiment 1, in which participants traversed the triple T-maze while performing an auditory Stroop task, only showed a trend in reducing alternation behaviour. We had hypothesized that, due to the detrimental effect of the dual-task on remembering the previous turn, participants would show less alternation. This expectation was based on the suggested role of memory in SAB (Lalonde, 2002). Given the non-significant result, however, it remains unknown how dual-task requirements influence alternation behaviour. Based on the obtained data we can only declare that if increased cognitive load does reduce alternation behaviour, the effect is likely to be small. One possible explanation, accounting for the absence of a significant effect, is that the auditory Stroop task was not difficult enough to impair participants' attention sufficiently. Although participants often reported being completely unaware of where they had walked to in the dual-task condition, using an even more engaging task could help reveal the targeted effect. Other ways to improve the power of the experiment would be the increase of the sample size or the use of a larger maze to achieve a more precise estimate of individual alternation rates.

Interestingly, an alternation rate of around 60% was also found in the congruent condition of experiment 2. In experiment 2, participants passed through a T-maze in three different conditions (Fig. 15c). In the congruent condition, participants physically and visually experienced a curved forced turn before arriving at the T-junction. At the T-junction, participants alternated direction with a significant rate of 61%. This suggests that walking adults alternate directions at similar rates independent of whether the forced turn prior to a T-junction is a curved, "graduate turn" as in the congruent condition of experiment 2, or an abrupt 90 degree turn as in experiment 1 (alternation rate of 58.3%). The finding is insofar notable as the classical study of SAB is restricted to sudden, abrupt turns. Showing alternation for a more drawn-out, continuous rotation provides an insight into the flexibility of SAB in humans. Despite the tendency to alternate directions in the congruent condition, neither the exclusively visual nor the exclusively physical condition showed the expected effect on alternation rates. We had hypothesized an increase of alternation in the visual condition and a decrease of alternation in the physical condition. The results, however, showed an identical, non-significant decrease in both conditions. In the subsequent exploratory analyses, the alternation rates in both conditions were shown to be not significantly different from 50%. Therefore, it remains unclear whether the exposure exclusively to the visual or physical component of a forced turn is sufficient to evoke any kind of alternation response. Although of speculative nature, one possible interpretation of this finding is that both the physical and visual component of a turn are necessary to trigger an alternation response.

The observation of small or absent alternation rates recurred in experiment 3. In experiment 3, participants walked through the open maze, which measures alternation of direction in an open area (Fig. 15d). We had hypothesized an alternation of direction based on comparable experiments performed on arthropod species (Barnwell, 1965). However, participants did not show a significant tendency to alternate their chosen direction in the open area relative to the initial forced turn. As visible in Fig. 18, the mean reverse turning angle at a distance of three meters lies very close to zero (mean value of 1.46 degrees). The curve shown in Fig. 18 seems to be slightly U-shaped. Whether this shape is simply due to random noise or whether it expresses a specific walking pattern cannot be determined based on the obtained data. Possibly, the oscillating motion of the head while walking played a role in the generation of the U-shape.

Often participants followed the trajectory they were on when leaving the corridor and continued walking straight into the open area. The non-significant finding stands in contrast to the result of the performed pilot experiment, in which a significant mean reverse turning angle of 7.6 degrees was found (using a sample of 30 participants). Again, the much larger sample size of the present investigation makes the estimates presented here more trustworthy and representative of the studied population. Finally, the tested correlation between digit repetitions in the Mental Dice Task and the reverse turning angles was not significant (Fig. 17). Also, no correlation was found between digit repetitions and the individual alternation tendency in the triple T-maze. The correlation tests were intended to uncover a potentially fundamental, modality-independent process of serial control in living organisms. As considered by Devenport (1983), SAB could have developed during evolution to prevent stereotyped, especially perseverative behaviour in long and unreinforced response sequences. Viewed from such a broad perspective, the avoidance of turning in one direction on consecutive choice points and that of repeating a particular choice on a cognitive level could well rest on one common ground, i.e. the protection from perseveration. Our findings offer little evidence for such a common denominator. One possible shortcoming of the present research design that may have prevented us to provide relevant evidence is the narrow definition of “repetition avoidance” in the 6-digit randomization task. In future, we plan to consider more in-depth analyses, not only including repetitions on immediately consecutive trials, but also those separated by gaps of variable length between a particular response and its first recurrence (Smith Jr., 1949). In the meantime, the non-significant correlation between locomotor and cognitive alternation found in the present experiment makes a conclusive decision difficult. Future research should more thoroughly investigate the relationships between SAB and diverse phenomena of an organism’s avoidance reactions in the face of repetitive events. Candidates are the inhibition of return (Klein, 2000), repetition suppression (Larsson and Smith, 2012), negative priming (Neill, 1997) and other types of inhibition as they manifest themselves in a broad range of cognitive domains (Dagenbach, 1994).

While the main motivation to investigate SAB in walking humans stems from an interest in basic psychological research, SAB is also of potential interest to the VR community. As briefly described in the Introduction section and concretely explored in experiment 2, it is possible to manipulate users in their walking trajectory by distorting the translation of physical movements into virtual movements. This technique, generally known as “redirected walking”, can be used to guide users away from walls in a physical room in order to allow the exploration of large virtual environments (Razzaque, Kohn and Whitton, 2001; Hodgson and Bachmann, 2013). Modern redirected walking algorithms apply redirection in an adaptive and dynamic fashion, taking into account the position of the user in the physical and the virtual world (Nescher, Huang and Kunz, 2014). One promising extension in the efforts to increase the efficiency of redirection is the incorporation of future pathway predictions. These predictions can be based on restrictions given by the virtual environment, such as corridors and forced turns, but also on inherent walking patterns of the user (Zmuda *et al.*, 2013). SAB represents one potential and hitherto neglected walking pattern to base such predictions on. From this perspective, SAB in humans may be of considerable interest to VR developers. Specifically for the case of redirection, it is key whether an imposed, purely physically perceived turn, as it was studied in experiment 2 (physical condition), is sufficient to affect the direction decision at an upcoming junction. Given the rather weak alternation rates found in that condition, caution seems warranted. But given the preliminary explorations we had undertaken here, there is still some potential in considering technical applications of SAB to the world of VR.

Notable is the absence of any significant side preferences in our T-mazes or in the open maze (exploratory analyses). Such have previously been described in physical environments (Mohr *et al.*, 2003). Moreover, also for these lateral biases gender differences have been reported (Bracha *et al.*, 1987; Mead and Hampson, 1996), which were not found in the present research. This may point to principal differences in human locomotion in real vs. virtual environments.

In summary, the present experimental series confirmed the notion of a general bias in humans to alternate directional choices in corridor-based virtual environments. This bias is weak compared to the vertebrate alternation bias commonly observed during real locomotion (Dember and Richman, 1989). Moreover, it seems to be restricted to the classic setting of T-junctions and does not extend to a more unrestricted directional choice in an open area. Unlike the situation of arthropod behaviour (Barnwell, 1965), assessing SAB as a continuous measure would not seem to be statistically useful in human subject research (Czaczkes, 2018). We hope that the present study will serve as a springboard to future investigations of locomotor sequential biases in walking adults. While we have probed SAB under rather restricted, artificial circumstances, future investigators may wish to study it under more natural conditions of veering and turning (Schaeffer, 1928; Souman *et al.*, 2009). Especially when facing much larger environments, or when pursuing ecologically relevant tasks such as finding a specific location, predictive walking patterns such as SAB may be more prevalent.

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Founding source

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Data availability and stage one protocol

The data collected in this study and the used analysis script are published on the Figshare repository (https://figshare.com/projects/Walking_through_virtual_mazes_Spontaneous_alternation_behaviour_in_human_adults/67643). The stage one protocol of the study is available on the Open Science Framework (https://osf.io/h2fkp/).

PART III

GENERAL DISCUSSION

13 General discussion

In this section the performed empirical studies and the obtained results shall be discussed in more detail. In order to not repeat the contents of the Discussion sections of the individual manuscripts I would like to focus on some of the aspects often faded down in published papers. Specifically, the limitations of the studies and encountered issues will be examined. Additionally, some of the methodological details will be inspected more thoroughly.

13.1 Estimating redirection thresholds

The estimation of redirection detection thresholds was one of the key aspects of the performed studies. This was especially the case for the studies of the first segment ("Redirected walking detection"). In total, the first segment included the estimation of redirection thresholds of 60 participants under different conditions. Fig. 19 gives a visual overview of the obtained thresholds.

As can be seen in Fig. 19 the obtained redirection thresholds are distributed on a range of 0.02 to 0.2 gain units, which corresponds to a curvature radius range of 50 - 5m (stronger redirection corresponds to a curve with smaller radius). Each participant was tested in two walking speed conditions (slow and fast walking). For both walking speeds, a detection threshold for leftward and rightward redirection was estimated. This results in the four detection thresholds shown for each participant. While the walking speed condition is indicated by colour, the curvature direction is not represented in the plot. As it turned out, there was no significant effect of curvature direction on redirection thresholds and for simplicity it is not further considered in the figure. One thing to note is the difference in variability of thresholds between participants. For some individuals the estimated thresholds lie very close to each other. In other cases, however, the thresholds span over a wide range of redirection intensities. There are different possible explanations: One possibility is a difference in performance-consistency between participants. The redirection threshold estimation took a duration of more than two hours and was divided into two separate sessions. Thus, it is likely that some participants were more consistent in their performance than others.

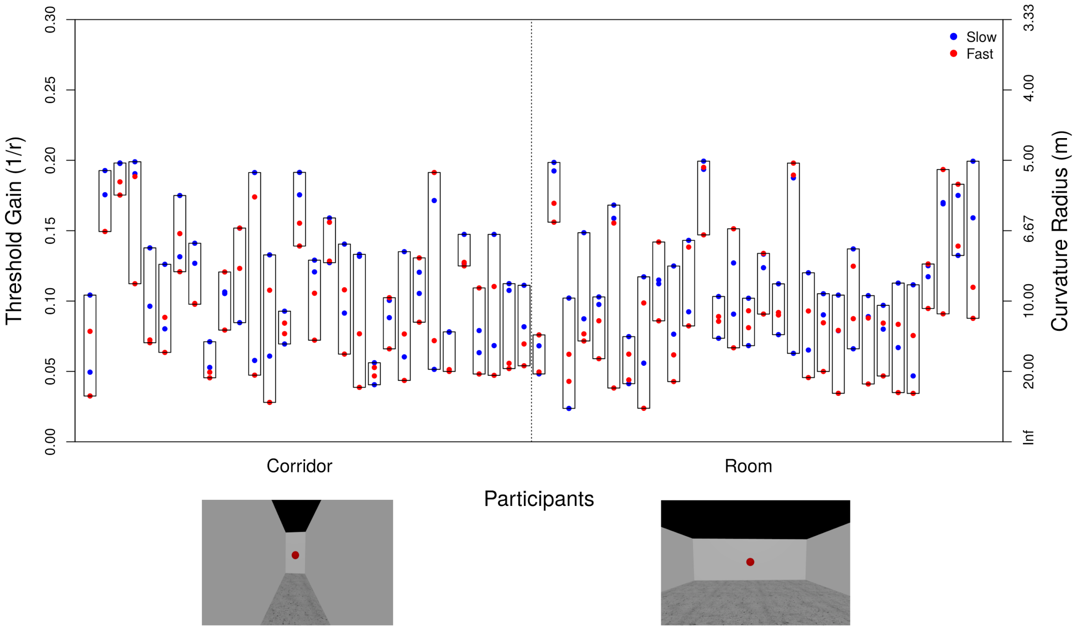

Fig. 19: Detection thresholds of redirected walking. Each column along the x-axis represents one participant. For each participant there are four data points, which are the leftward and rightward redirection thresholds for slow and fast walking. On the y-axes the redirection intensity is shown in gain units (left side) and associated curvature radii (right side). Participants are divided into two groups, corresponding to the type of virtual environment, in which the experiment had been completed (corridor/room).

A lack of consistency could lead to the observed variability in redirection thresholds. Another possibility are person-specific effects of curvature direction on redirection thresholds. For some participants it might be that for example leftward redirection is much easier to detect than rightward redirection. A large curvature direction effect would make a participant's thresholds span a larger range of redirection intensities. Lastly, it could be the result of inherent variance of the applied estimation method. We had used 40 trials for the estimation of one threshold, which resulted in 160 trials for each participant. Although this amount of trials is expected to yield a somewhat reliable estimate of true thresholds (Karmali *et al.*, 2016), more trials would naturally improve the final estimation. Interestingly, despite the difference in variability between participants, it is possible to recognize the effect of walking speed in the plot. The fast-walking thresholds (red dots) seem to generally lie lower than the slow walking thresholds (blue dots). This impression was confirmed in the formal analysis of the data. The beneficial effect of fast walking for redirection detection was not a complete surprise. One previous study had already reported a walking speed effect on redirection thresholds, albeit using a slightly different approach to control walking speed (Neth *et al.*, 2012). In fact, many of our participants spontaneously reported after the experiment that fast walking had facilitated detection for them. In contrast to the walking speed effect, no significant effect of the environment size was found. As can be seen in the plot, there is no clear difference between the thresholds obtained in a narrow, virtual corridor (left) and a wider, virtual room (right). Suspicions expressed by VR researchers about the existence of such an effect had originally caused us to include the factor in our study (Hodgson, Bachmann and Thrash, 2014). Therefore, it was a somewhat disappointing result. However, unlike the walking speed, environment size was only tested as a between-subject factor. The decision to have environment size as a between-subject factor was due to considerations of the highly increased experiment time associated with a third within-subject factor. Naturally, the power to uncover an effect of environment size was greatly reduced due to the between-subject design.

Not visible in the above discussed plot is the tested relation between psychological traits and redirection thresholds. The main finding consisted of a negative correlation between visual dependency, measured with the rod-and-frame test, and redirection sensitivity (see Fig. 5, page 51). As discussed in the respective study, the rod-and-frame test performance stood out among all the tested traits in terms of its significant relation with redirection thresholds. This raises the hope that indeed it is visual dependency, which is a strong predictor of redirection sensitivity. Given such a relation, the rod-and-frame test could be used as a quick assessment tool of a user's redirection threshold prior to a VR experience. However, it remains questionable, whether the observed correlation is strong enough to allow a satisfactory prediction of redirection sensitivity ($r = 0.48$). In addition, caution must be used in the interpretation of the obtained p-values. The design of the respective study was of exploratory nature. Although backed up by theoretical considerations and associated hypotheses, there was a wide range of effects tested. The p-values obtained for these tests were not corrected for multiple comparisons. Given these circumstances, a replication is clearly required to confirm the relation between visual dependency and redirection sensitivity.

Independent of the obtained results, we were satisfied with the threshold estimation procedure. In the introduction to this thesis I spent a large part outlining the motivation behind the used 2AFC estimation approach, implemented in the QUEST function (Watson and Pelli, 1983). Fortunately, participants did not have issues following the 2AFC procedure and the threshold estimation ran smoothly. The main advantage of the 2AFC procedure is the elimination of subjective biases. Given this advantage, the here presented redirection thresholds are expected to be a trustworthy representation of the true redirection sensitivity in our study population.

However, despite all efforts, we do suspect that a small bias sneaked into our procedure after all. Although the 2AFC method cannot be made directly responsible for the bias, it is connected to the testing structure dictated by the 2AFC approach. In our implementation of the 2AFC approach the participants walked two times towards a virtual target. Only in one of the two trials, redirection was applied. The task was to point out afterwards whether redirection had taken place in the first or second trial. There is reason to believe that participants showed a difference in sensitivity depending on whether redirection took place in the first or second trial. This is shown in our data, where we have more correct answers for runs where the stimulus was in the second trial. Comparing the detection rates between cases with redirection in the first vs. the second trial, revealed a significantly higher detection in the latter case (paired t-test, $t = -3.35$, $df = 59$, $p = 0.001$).

Possibly, the long time duration of a trial explains the found bias. Participants seem to have more difficulties detecting untampered walks as opposed to detecting redirected walks. Thus, in cases where the redirection takes place in the first trial, the memory of the experienced manipulation could be slightly blurred at the time of answering. Naturally, such a bias would violate the assumptions underlying the 2AFC procedure, in which it is expected that sensitivity stays constant independent of the trial. However, despite this potential flaw, I believe the benefits associated with the 2AFC method make the used approach favourable over conventional methods.

In addition to potential biases, the suitability of the applied QUEST function was examined. QUEST uses a Bayesian framework to fit a psychometric function to the answers of participants. This fit is used to estimate the detection thresholds. One key assumption of the QUEST function is an identical slope in the psychometric functions of different participants. To test this assumption, a model was fitted to our obtained data using a flexible slope parameter, allowing to fit an individual slope for each participant. A likelihood ratio test, comparing the model with flexible slope to the original model revealed a significantly better fit in the former case ($LR = 292.9$, $df = 59$, $p < 0.001$). Therefore, the finding indicates a violation of the identical slope assumption of the applied model. However, the result has to be evaluated with caution. Due to the adaptive nature of the threshold detection, the trials only included redirection intensities very close to the detection threshold of each participant. Due to the limited range of tested stimulus intensities, the maximum likelihood fit using a flexible slope runs danger of over-fitting the data. This is visible in the proposed slopes of the model, which include for the most part extremely steep slopes. Steep slopes propose very clear-cut thresholds in detection, which is rather unlikely in reality and is indicative of over-fitting. A more insightful analysis of the applied model could be achieved by using a more outstretched range of tested redirection intensities for each participant.

A final remark concerns the statistical analysis in the first segment. The statistical analysis was separated into two steps. In the first step, the redirection thresholds were determined based on the 2AFC answers. Subsequently, the obtained thresholds were used as the target variable in a mixed model approach to test relations with various variables. However, it would have been possible to combine the two steps into one big model, fitted directly to participants' answers in the 2AFC task. The advantage of such an approach is that the uncertainty of the threshold estimation is preserved throughout the analysis.

To test this approach, I fitted an all-embracing model to the 2AFC answers, testing the relation between redirection sensitivity and the reported variables in the first segment. The model was fitted using the Bayesian statistics extension Rjags for the statistical software R (Plummer, 2018). The model formulation and the obtained results are reported in the Appendix (page 154). In summary, the results replicated the positive effects of walking speed and rod-and-frame test performance indicated by the originally used two-step analysis (Nguyen *et al.*, 2018; Rothacher *et al.*, 2018). Interestingly, the Bayesian analysis also revealed negative effects on redirection sensitivity of the *blindwalking angle sd*, the *curvature direction* (higher sensitivity for leftward redirection) and a positive effect of the *SSA score*. These effects were not indicated in the original, two-step analysis. A negative relation between redirection sensitivity and blind veering (expressed by the *blindwalking angle sd* variable) is what we were originally expecting (Kallie, Schrater and Legge, 2007). Similarly, a positive relation between somatosensory sensitivity/amplification (expressed by the *SSA score*) and redirection sensitivity would agree with our original hypothesis. In contrast, a general advantage in detecting leftward curvature compared to rightward curvature was not expected. Although these findings shine a new light on the data, the results must again be interpreted with caution. The Bayesian analysis underlying these results is more sophisticated but also more complicated and complex than the originally used two-step analysis. The complexity of the applied method makes it difficult to ensure that the estimated posterior distributions are trustworthy. In Fig. 20 on page 157, the posterior sample chains are presented and it can be seen, that in some cases the algorithm did not produce a clean estimate of the posterior distribution (e.g. in the coefficient of the *SSA score*). Thus, there is still room for improvement. One possible solution would be the collection of even longer sample-chains. Although an increase in chain length should secure a better estimation of the posterior distributions, the approach would require very large computational demands and computation time, a resource whose limits I have started to reach given the hardware available to me. See page 154 in the Appendix for a more detailed description of the applied Bayesian analysis.

13.2 Hardware issues and motion sickness

The goals of the second segment were in many respects similar to the first one. Again, the aim was to determine redirection thresholds under various conditions. This time, however, it was of interest how the used perspective and the synchrony between one's movements and an avatar's movements affected redirection sensitivity. In terms of the obtained results, the study was unfortunately rather disappointing. Neither an effect of perspective nor an effect of movement synchrony could be shown. As usual, the inability to reject a null hypothesis does not leave many insights except that if there is an effect, it was most probably too small to be detected with the power of the performed experiment. This time we kept both factors of interest as within-subject factors. But we had only recruited 30 participants. Although none of the main effects of interest were shown, we did find a significant correlation between the experienced feeling of agency and redirection thresholds. Thus, independent of the condition, participants with a stronger feeling of agency performed better in the detection task. As described in the respective study, the interpretation of this finding is difficult. The main idea behind the alteration of movement synchrony with the avatar was to manipulate the feeling of agency. Although this manipulation has worked (based on the questionnaire ratings), no effect of the movement synchrony on redirection thresholds could be shown. Given the absence of a significant main effect of the condition it is unclear how the correlation with the feeling of agency must be evaluated. It is especially problematic to infer any kind of causal relationship between the feeling of agency and redirection sensitivity based on this result. How the feeling of agency and redirection sensitivity truly relate to each other can only be determined with new, higher-powered studies.

In addition to the problem of the interpretation of the results, the study did suffer of other problems as well. To have an avatar in the virtual scene required the use of a body-tracking suit. This allows the mimicking of the participants' movements by the avatar. However, the used hardware turned out to be not fully appropriate for the purpose. It is possible that the used body tracking device ("perception neuron" tracking suit) is rather intended for stationary body tracking. Walking around with the suit would eventually lead to a drop in the tracking quality. Over time this resulted in a distorted body position of the avatar. Also, the movements of the user would no longer be represented properly. In addition, the software of the tracking suit had to be combined with the position tracking software used for the redirection. This combination also produced some issues which undermined the quality of the virtual presentation. The only solution to keep body tracking at an acceptable quality was to recalibrate the suit repeatedly during the experiment. The recalibration, however, led to interruptions of the experiment and it is difficult to assess how these breaks affected the participants. All in all the work with the motion tracking suit turned out to be rather frustrating for the participants and even more for us, the experimenters.

As if there were not enough problems with the motion tracking, the 3PP redirection brought its own difficulties. In the conventional 1PP redirection, participants seemed to tolerate the manipulated visual feedback very well. In the experiment of the first segment, only one out of 61 participants had to stop the participation due to a feeling of uneasiness and motion sickness. With regard to the experiment duration (in total more than two hours) and the extent to which motion sickness is still a problem in VR, this rate can be regarded as acceptably low. For the 3PP redirection, however, there was no prior implementation available and we had to devise it from scratch. A first step consisted of figuring out how the camera had to react to head movements. Also, it had to be determined around which axis the camera had to rotate to achieve the intended walking curvature. When we started testing participants for the agency study, we used a first version of the 3PP redirection. In the first version, however, head movements of the user would not result in any movement of the virtual scene, but only in the avatar moving its head in synchrony. Piloting trials with the setup seemed to work fine, but these trials were mostly conducted on ourselves or associated researchers. While testing naive participants with the setup, we quickly realized that it triggered a feeling of motion sickness in many cases. The misjudgement of the tolerance of our participants would immediately become evident. The early termination of the experiment seemed inevitable when we had to report a drop-out rate of 50% after the first six participants, with one of the participants vomiting on the floor during the experiment. As a last resort, we tried an adjustment of the camera behaviour. This turned out to make the experiment much more tolerable, and we could finish the study with 30 new participants. As a summary, the agency study was everything else but a smooth procedure. Different factors may be responsible for the problems of this study. One of the main issues was that the entire study had to be conducted in a rather limited time frame. The time pressure was due to the upcoming end of the project's runtime. A more extended piloting phase might have prevented some of the encountered issues.

13.3 SAB and the registered report format

Somewhat in stark contrast to the experience of the agency study, stands our investigation into spontaneous alternation behaviour. Of all conducted studies the second SAB study felt the most rewarding and enjoyable. The enjoyment, however, did not necessarily stem from the obtained results. Most of the tested hypotheses could unfortunately not be rejected. Although in general we did show significant alternation behaviour, the alternation frequency was smaller than expected (ca. 60%). The assumed influence of an increased cognitive load on alternation rates could unfortunately not be demonstrated. Also the effects of the visual and bodily component of a forced turn on subsequent alternation tendencies were not conclusively determined. At last, we did not succeed in demonstrating a relation between repetition avoidance in random number generation and SAB. Nevertheless, the study succeeded in its original goal, which was to pick up the thread of human SAB investigation. Despite the negative results the study does give a good insight into the presence and characteristics of SAB in humans. It is, however, difficult to assess at this point, whether SAB will ever be used as a means to improve redirected walking. Perhaps more flexible models might be better suited to predict future direction choices of walking humans. Such models could make use of a wider range of predictors instead of only the previous turn direction when estimating future pathways. Additional predictors could not only be the direction choices at earlier junctions but also other variables such as the position inside a corridor, eye movements, the nature of concurrent tasks, visual characteristics of the maze arms, etc.

What I found most satisfying in the SAB study was the format of the publication. We chose to submit the SAB study as a registered report to the journal “Cortex”. Up to this point, our team had only limited experience with the format. Coincidentally, the motivation to try the format came from a conference talk by Prof. Chris Chambers who is an editor at Cortex. In the talk he presented the idea of registered reports. In fact, Prof. Chambers had been one of the leading figures in the development of the format (Chambers, 2013). The main idea behind a registered report is that a manuscript is submitted before any data are collected. The manuscript only includes an introduction section and a method section. In the manuscript the experimental design has to be outlined and the analysis pipeline defined. All tested hypotheses must be clearly stated beforehand. This first submission undergoes peer review, in which it is judged exclusively by the methodology and the research questions. If they are regarded as fulfilling the quality requirements of the journal, the submission reaches stage one approval. Stage one approval basically equals a promise of publication, independent of how the results turn out to be. Subsequently, the experiment is conducted and the final manuscript with results and discussion sections is handed in. The introduction and method sections from the first submission are not allowed to be changed in any way. Another peer review round is conducted, in which the added sections are judged. The goal of the procedure is to prevent any kind of statistical trickery, retrospective change of hypotheses, publication bias, and many more known problems of the publication process.

The strict requirements regarding the statistical planning forced us to come up with a clear set of hypotheses. All statistical tests had to undergo a thorough power analysis. This forced us to truly choose an appropriate sample size. Because some of the effects we aimed for were expected to be of small size, we reached a very high sample size for the experiment. 288 participants had to be tested in total to reach the required power. Luckily, however, there was only a testing duration of 10 minutes per participant and we had enough budget left to offer a 10 franc reimbursement for the participation. Due to time pressure, we were forced to conduct the study as fast as possible. Finally, we managed to conduct the whole data collection within one and a half month, sometimes testing up to 25 participants a day. Despite the stressful data collection, the working process of the study was comfortable. Especially once stage one approval was obtained, we did not have to worry about the final results. Instead we could focus entirely on the conduction of the experiments. Also, once the data were collected, we could simply run it through the already accepted analysis pipeline. Especially for a study like the SAB investigation, where the outcome of the results was largely unsure, the process of the registered report made our work much more pleasant.

13.4 The collaborative effort

The common thread throughout the project was the idea of a bilateral profit for both involved research fields. Psychology and VR research were supposed to benefit form the conducted studies in an equal manner. With all the experiments completed and for the most part published, the outcome of the reciprocal exchange shall be summarized here. The first segment of the project focused on the determination of redirection thresholds. This was predominantly an investigation fuelled by an application-oriented motivation. As such, the study seemed to be mainly benefiting the VR research field. The demonstration of a walking speed effect was an important confirmation of a finding for the VR literature. Testing an effect of environment size and gender on redirection sensitivity was also of interest mainly to a VR audience. However, investigating the role of visual dependency in redirection sensitivity brought a more psychological perspective to the matter. As a contribution to the issue of multisensory processing and action monitoring in locomotion, it was of interest to a broader audience. By pointing out how redirection lines up neatly with current agency research, the case was made about the value of redirection for psychological research. At the same time, showing a relation between the performance in the rod-and-frame test and redirection thresholds, was valuable for the VR community as well. Although it is unclear whether the rod-and-frame test will ever be used in VR applications, the inquiry does touch a key issue in VR development. The mismatch between visual and bodily feedback is not only of importance in redirected walking. It is much rather a general issue in VR applications. The mismatch exists every time a virtual action is presented without the person physically performing that action. As such, it is likely that the study of how users process and react to such an exposure, will only become more important in the future. Especially in light of the importance of sensory mismatches for consumer satisfaction (e.g. motion sickness), every advancement into the underlying psychology can become valuable. Thus, it seems that the first segment truly did achieve a mutual benefit for both research fields.

The study of the second segment is a bit more difficult to evaluate. The goal was to test an effect of perspective and movement synchrony on redirection sensitivity. The language of the study focused somewhat heavier around psychological concepts, like for example the feeling of embodiment and the feeling of agency. As such, the study seemed to be rather intended for an audience with an interest in psychology. However, the study did not reveal the effects it had aimed for, and thus the benefit is difficult to assess. The point can be made, that actually it is the VR community who profits most from the study. The third person perspective is heavily neglected in VR applications. However, there is a development of using 3PP in VR. Especially in the entertainment sector there have been very successful implementations of 3PP in VR applications. Given a trend to 3PP in VR, it is very likely that the focus also turns to redirected walking in 3PP. Questions about whether redirection can be applied in 3PP and how users perceive such redirection would become pressing. In this light, our implementation of redirection in 3PP and the corresponding redirection threshold estimation are a valuable contribution to VR research.

Finally, I turn to the SAB segment. The main goal of the SAB studies was to demonstrate the presence of SAB in walking users and to examine the underlying mechanisms of the behaviour. From a VR perspective, the hope was that the principle of SAB could be used as a tool to predict future walking pathways of users. Predictions about future pathways could be used to improve redirection efficiency. However, given the rather small magnitude of the found alternation rates, it is questionable whether such an application will ever become a reality. In light of the small size of the found effects, and the absence of significant effects otherwise, the benefit for VR research remains limited. Thus, the study should rather be valued as a contribution to basic behavioural research about alternation behaviour. In this regard it is a comprehensive and technically sound investigation of the phenomenon of SAB and offers many new insights. Therefore, the benefit of the third segment is rather located on the psychological side of the collaboration. The study can, however, still be of value as a steppingstone for future investigations of pathway prediction for VR applications.

As can be seen, the benefits for the two research fields did not always get distributed in the individual studies as one might have predicted in the beginning of the project. In general, however, the project did mostly live up to the expectation of a mutual advancement. The mutual benefit is also represented in the produced publications, which consisted of multiple papers published both in VR conference proceedings and psychology-focused journals.

13.5 The future of redirected walking

It is unclear, how the foreseeable future of redirected walking will look like. The principle of redirection has so far only found limited application outside of research (Martindale, 2015). Whether this will change in the future is difficult to predict. The reason for the uncertain future of redirected walking is connected to the uncertainty about the future of VR in general. Presently, the applications and markets for VR are still developing and it is unsure in which direction VR will head. Whether VR will really become widespread for personal entertainment is not sure either. Possibly, it will rather find its place in applications used for training and educational purposes. In any case, VR has still some key issues to solve before a pleasant, regular usage is possible. One of the main issues is the problem of motion sickness. Even with a high refresh rate of the display the problem persists. This is due to the mismatch between perceived and performed movements. Therefore, the susceptibility to motion sickness is tightly connected to how virtual locomotion is enabled. Since the use of real walking minimizes the gap between real and virtual movements, redirected walking could become an attractive tool in the future. Possibly in combination with very large tracking areas redirected walking will find more regular application.

Apart from commercial applications, the question arises about the future of redirected walking in behavioural research. As demonstrated in this dissertation, redirected walking does have something to offer to the psychological sciences. Whether researchers will take up redirection as a tool to further study human perception is currently unclear. However, there have been some remarkable developments. For once, there is a high number of publications in the VR literature, which exhibit heavy focus on psychological questions regarding perception and cognition in VR. Thus, the trend of the two fields approaching seems to continue and is not a unique incident in this project. Second, there is a potential of using redirection and similar procedures in the clinical context. Action monitoring and awareness are linked to a range of neurological disorders (Fourneret *et al.*, 2001; Ursu *et al.*, 2003). Just recently, a group around Prof. Olaf Blanke has published a report in which the locomotor awareness of sleepwalkers in the awake state was tested (Kannape *et al.*, 2017). Locomotor awareness was tested using a setup, which resembles redirected walking to a remarkable degree. The authors found a difference in how sleepwalkers perceived the walking manipulations compared to healthy participants. This was the first time sleepwalkers could be differentiated from non-sleepwalkers in the awake state. Using our own redirection system we have recently started a study, in which we try to confirm and extend the found effects in sleepwalkers. At the time of the submission of this dissertation, the data collection of the sleepwalker study has been finished but the data analysis is still in process.

The future will show how useful redirected walking will be for psychology and possibly neurology. In any case, redirected walking is only one example of how VR can enable the study of processes which would be hard to recreate otherwise. Psychologists are presently still enlarging the potential of VR. It remains to be seen, whether new procedures similar to redirected walking will emerge in the future and possibly open the door for further interdisciplinary collaborations.

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PART IV

APPENDIX

15 Segment 3, study 2: **Randomization scheme**

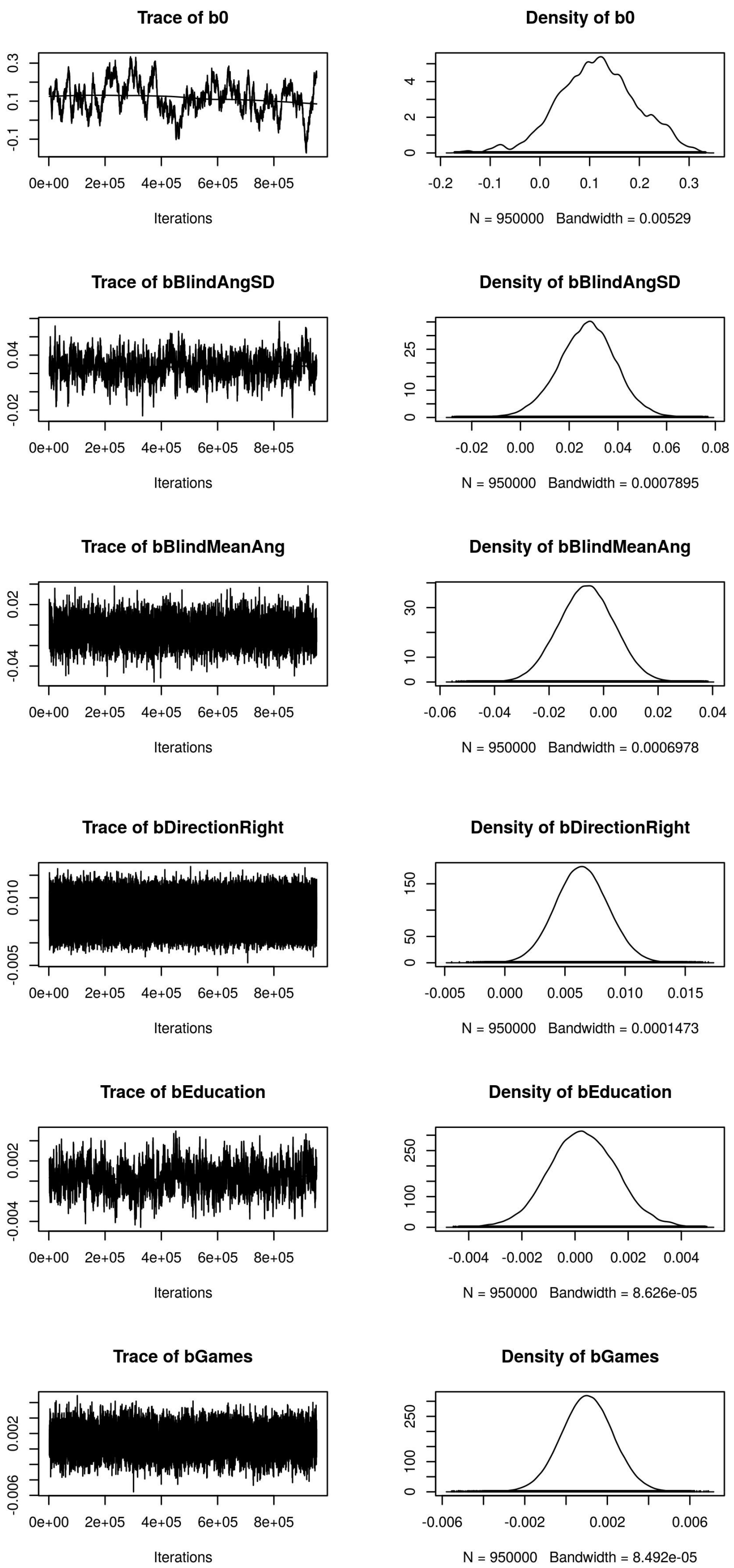
In total there were six trials for each participant to complete: one walk in experiment 3, two walks in experiment 1 and three walks in experiment 2. The main constraint to the randomization of the order of trials was that there are never two trials of the same experiment directly after each other. To this end the six trials were divided into two groups, group 1 containing the three trials of experiment 2 and group 2 containing the two trials of experiment 1 and the one trial of experiment 3. On this group-level, half of the participants followed the order “1,2,1,2,1,2”, while the other half followed the order “2,1,2,1,2,1” for the completion of the six trials.

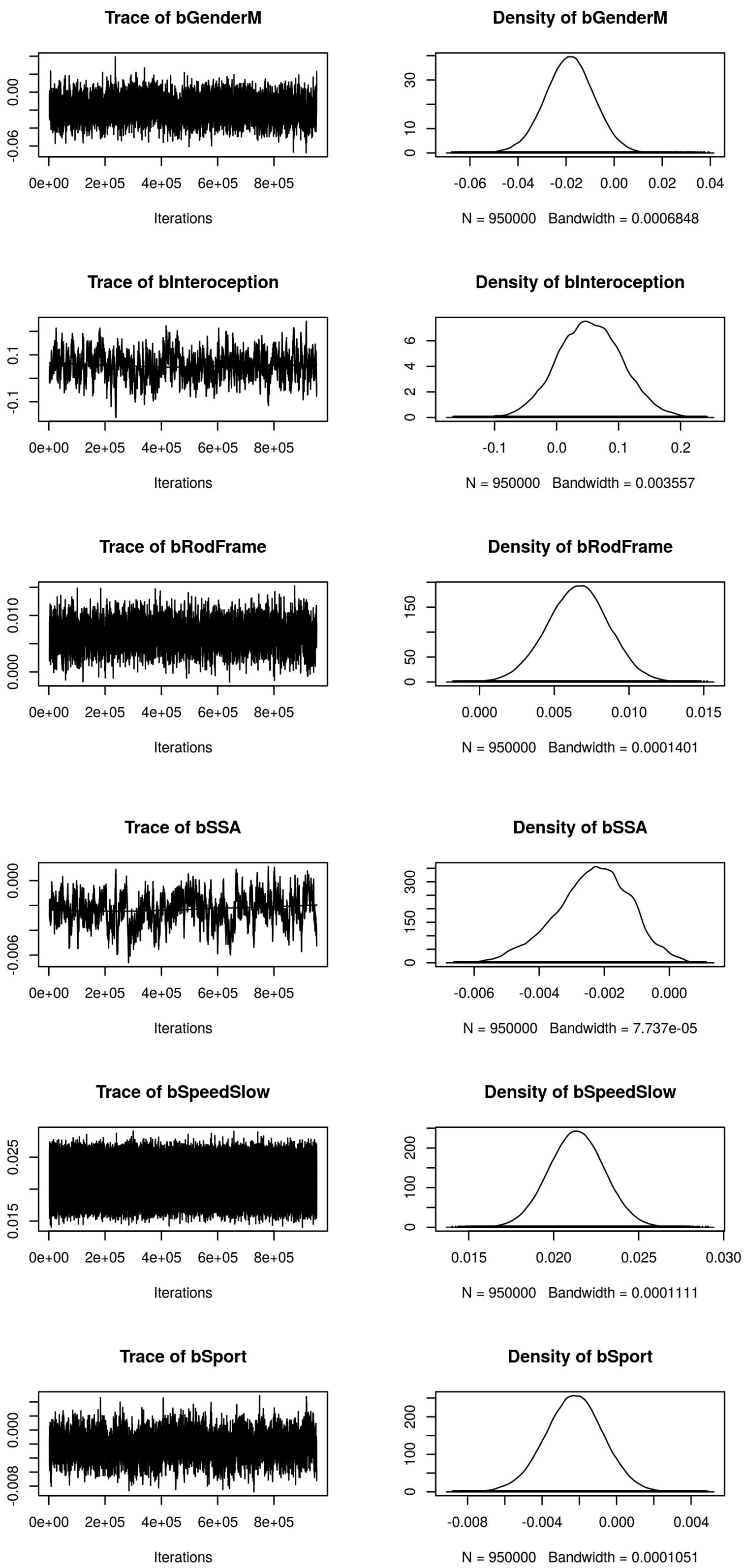
For the order “1,2,1,2,1,2”, the three trials of each group can be permutated into six different sequences, which leads to 6 x 6 = 36 possible sequences in total (e.g. exp3a, exp2b, exp3c, exp1, exp3b, exp2a). This is doubled when adding the 36 possibilities of the order “2,1,2,1,2,1”, leading to an absolute total of 72 possible trial sequences. We chose the number of participants to be 288, since this value lies above the required sample sizes based on the power analyses and is dividable by 72, allowing each of the 72 possible trial sequences to appear equally often.

In a second step the order of left and right forced turns was randomized over participants. In experiment 3 there were two possible configurations for the forced turn since there was only one trial (“L”, “R”). In experiment 1 there were four different configurations of forced turns possible since there were two trials (“L,L” , “L,R” , “R,L” , “R,R”). And in experiment 2 there were eight different configurations possible due to the three trials. Since 288 is dividable by 8 (and therefore also by 4 and 2), the different forced turn configurations appeared equally often for each experiment. Starting with the first participant, the forced turn configurations for each experiment were assigned randomly using sampling without replacement from all possible configurations and starting again once all configurations were used up (after two participants for experiment1, four participants for experiment 2 and eight participants for experiment 3).

16 Bayesian analysis of redirection sensitivity

The participants answers to the 2AFC questions in the redirection threshold estimation were modeled using a psychometric curve based on the Weibull function (Watson and Pelli, 1983). To examine the linear relation between the variables of interest and redirection thresholds, the horizontal position of the psychometric function (using a logarithmic scale of redirection intensity as an X-axis) was modeled as a linear combination of the tested variables (and an intercept). Using the Bayesian-analysis extension Rjags, samples from the posterior distributions of the variables' coefficients were drawn using a Markov chain Monte Carlo method (MCMC). The complete Rjags-code including the formula of the psychometric function is given below. The drawn sample-chain consisted of 950'000 samples for each coefficient with a preceding burn-in period of 1'000 samples. The obtained sample traces and the therefrom estimated posterior distributions are presented in Fig. 20. The corresponding 95% highest density intervals of the tested variable coefficients are shown in Table 5. The results show significant effects of walking speed and the rod-and-frame test performance. These effects were also found using the original two-step analysis. Additionally, the Bayesian analysis indicates positive effects of the *blindwalking angle sd*, the *curvature direction* (higher sensitivity for leftward redirection) and a negative effect for the *SSA score*. However, these findings must be interpreted with caution since some of the traces show very strong autocorrelation. For example the traces of the *Intercept*, the *SSA score* and the *Sway Romberg quotient* did not result in clean posterior distribution densities. Using even longer sample chains could help to average-out the autocorrelative pattern and achieve a cleaner estimate of the posterior distributions.


Trace of b0
Density of b0
Iterations
N = 950000 Bandwidth = 0.00529
Trace of bBlindAngSD
Density of bBlindAngSD
Iterations
N = 950000 Bandwidth = 0.0007895
Trace of bBlindMeanAng
Density of bBlindMeanAng
Iterations
N = 950000 Bandwidth = 0.0006978
Trace of bDirectionRight
Density of bDirectionRight
Iterations
N = 950000 Bandwidth = 0.0001473
Trace of bEducation
Density of bEducation
Iterations
N = 950000 Bandwidth = 8.626e-05
Trace of bGames
Density of bGames
Iterations
N = 950000 Bandwidth = 8.492e-05


Trace of bGenderM
Iterations
Density of bGenderM
N = 950000 Bandwidth = 0.0006848
Trace of bInteroception
Iterations
Density of bInteroception
N = 950000 Bandwidth = 0.003557
Trace of bRodFrame
Iterations
Density of bRodFrame
N = 950000 Bandwidth = 0.0001401
Trace of bSSA
Iterations
Density of bSSA
N = 950000 Bandwidth = 7.737e-05
Trace of bSpeedSlow
Iterations
Density of bSpeedSlow
N = 950000 Bandwidth = 0.0001111
Trace of bSport
Iterations
Density of bSport
N = 950000 Bandwidth = 0.0001051

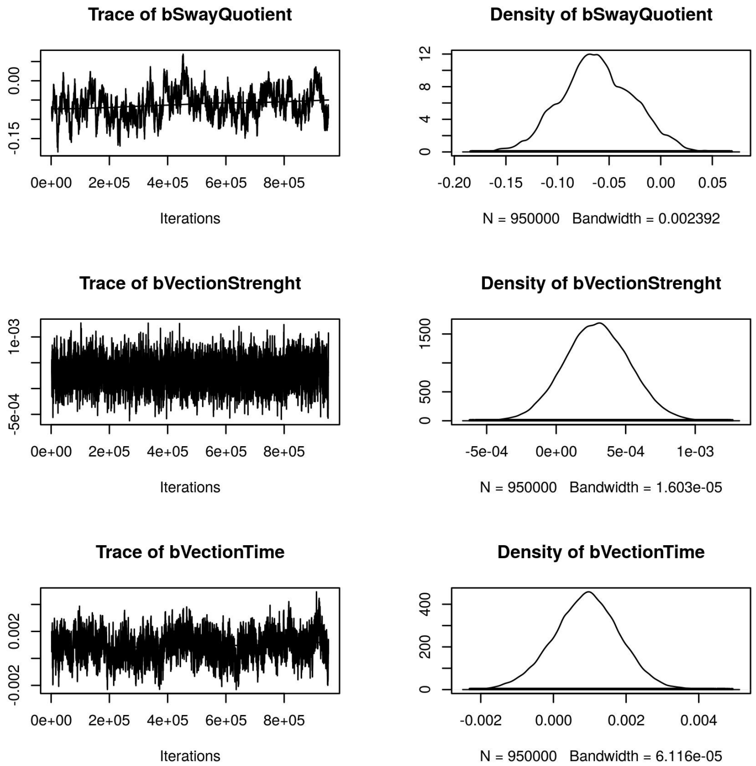


Fig. 20: Traces and densities of the MCMC posterior distribution samples of the examined variables.

Variable	Coefficient's 95% highest density interval
Intercept (b0)	-0.0299, 0.2782
Blind-walking angle sd	**0.0026, 0.0508**
Blind-walking mean angle	-0.0265, 0.0138
Curvature direction (right)	**0.0021, 0.0107**
Education	-0.0022, 0.0029
Video-gaming per week	-0.0015, 0.0035
Gender (male)	-0.0386, 0.0018
Interoceptive sensitivity	-0.0497, 0.1560
Rod-and-frame mean angle	**0.0024, 0.0106**
SSA score	**-0.0047, -0.0001**
Walking speed (slow)	**0.0182, 0.0246**
Sport per week	-0.0054, 0.0008
Sway Romberg quotient	-0.1275, 0.0101
Vection mean strength	-0.0001, 0.0007
Vection mean onset time	-0.0010, 0.0027

Table 5: 95% highest density intervals of the examined coefficients. Intervals, which exclude zero, are highlighted in bold.

16.1 Rjags code

```
model{
   gamma ← 0.5
   beta ← 3.5
   natLogFac ← 0.4342945 #to switch from natural log to log10 (no function in jags!)
   eps ← natLogFac*log(-log(0.5))/beta

for (i in 1:N){
         answer[i] ~ dbern(theta[i])

         theta[i] ← 0.9999999999-(0.9999999999-gamma) * exp(10^((beta) * (natLogFac * log(gain[i])
         - natLogFac*log(T[i]) + eps))) #the 0.999999 is needed to prevent rounding issues
```

```
        T[i] ← b0 + bRodFrame*rodFrame[i] + bSpeedSlow*speedSlow[i] +
        bDirectionRight*directionRight[i] + bGenderM*genderM[i] + bSwayQuotient*swayQuotient[i] +
        bVectionTime*vectionTime[i] + bVectionStrenght*vectionStrength[i] +
        bInteroception*interoception[i] + bBlindMeanAng*blindMeanAng[i] +
        bBlindAngSD*blindAngSD[i] + bSSA*SSA[i] + bSport*sport[i] + bEducation*education[i] +
        bGames*games[i] + bParticipant[participant[i]]
        }

# (Non-informative) Priors:
for (j in 1:J){ bParticipant[j] ~ dnorm(0, precPart) }
precPart ← 1/(sigmaPart^2)
sigmaPart ~ dunif(0,100)

b0 ~ dnorm(0, 1E-6)
bRodFrame ~ dnorm(0, 1E-6)
bSpeedSlow ~ dnorm(0, 1E-6)
bDirectionRight ~ dnorm(0, 1E-6)
bGenderM ~ dnorm(0, 1E-6)
bSwayQuotient ~ dnorm(0, 1E-6)
bVectionTime ~ dnorm(0, 1E-6)
bVectionStrenght ~ dnorm(0, 1E-6)
bInteroception ~ dnorm(0, 1E-6)
bBlindMeanAng ~ dnorm(0, 1E-6)
bBlindAngSD ~ dnorm(0, 1E-6)
bSSA ~ dnorm(0, 1E-6)
bSport ~ dnorm(0, 1E-6)
bEducation ~ dnorm(0, 1E-6)
bGames ~ dnorm(0, 1E-6)
}
```