The Effect of Spatial Audio on Thresholds for Curvature Gains in Redirected Walking Applications in Virtual Reality

M.D.J.D. Gerritse
Department of Information Science
Utrecht Univeristy
Utrecht, The Netherlands
m.d.j.d.gerritse@students.uu.nl

Abstract—**Redirected walking (RDW) is a technique used in virtual reality (VR) applications to allow users to navigate virtual environments that are larger than the physical space they are walking in. RDW works by decoupling the user's virtual trajectory from their real trajectory, and is achieved by manipulating the view of the virtual world presented to the user via a head-mounted display (HMD). The success of this technique depends on the dominance of vision in orientation perception. However, there are limitations to how much the orientation can be manipulated before the user notices and the illusion is broken. This study aims to investigate the effect of adding spatial audio elements to RDW in order to increase the perceptual threshold and allow for higher levels of redirection while maintaining a convincing experience. This research conducts user experiments with a population of n=18, under conditions with and without spatial audio elements, to research the perceptual thresholds. The tested curvature gains range of 0°/m, 3°/m, 6°/m and 9°/m, to both the left and right. An increase in detection threshold of 2.56°/m is found between conditions with and without audio, which leads to a detection threshold of 8.7°/m when spatial audio elements are applied. This positive effect on thresholds could allow for higher levels of redirection when spatial audio is applied, while maintaining a convincing experience, leading to more freedom to navigate virtual environments in even smaller physical spaces.**

Index Terms—**Human Computer Interaction, HCI, redirected walking, virtual reality, locomotion, curvature gain, spatial audio**

I. INTRODUCTION

One of the fundamental challenges in VR applications is locomotion; i.e., how the user navigates the virtual world. When using natural body movement for virtual navigation, translating the users' movement in the real world to the virtual world poses the challenge of physical limitations, such as limited physical space and obstacles. One of the techniques to apply real movement to a virtual world is redirected walking (RDW) [Razzaque et al. 2001].

The aim of RDW is to "allow users to walk in virtual worlds which are of greater dimensions than the real physical space they walk in" [Razzaque et al. 2001]. RDW is a perceptual illusion that introduces subtle discrepancies between real and virtual motions to keep the user within physical space boundaries. Conventionally there is a 1-to-1 mapping of movement in the real world to the virtual world. RDW changes this relationship, it decouples the users' virtual trajectory from the real trajectory. This is done by manipulating the view of the virtual world, with every step the user takes, which can be achieved since the head-mounted display (HMD) fully blocks out the physical world and only presents the virtual environment to the user. The success of this illusion is reliant upon the dominance of vision in orientation perception. However, there are boundaries to how much the orientation can be manipulated before it is noticed by the user and the illusion is broken. This is a limitation of the concept of RDW in general.
This perceptual threshold has been researched before and is dependent on the applied RDW technique. Inspired by research carried out by Matsumoto et al. in 2016 on adding congruent stimuli [Matsumoto et al. 2016], this research aims to study the effect of adding spatial audio elements to an RDW illusion and subsequently measure the effect of this addition on the existing perceptual thresholds. The addition of spatial audio elements can confirm the illusion that the eyes are perceiving, and with that provide validation of the illusion to the brain. The current research aims to test if this addition allows for an increase in perception thresholds. In this study, user experiments with different conditions are carried out to research the perceptual threshold under multiple conditions.

Determining if there is a positive effect on thresholds could allow for higher levels of redirection while maintaining a convincing experience. If this can be achieved, this could lead to experiencing more freedom to navigate a virtual environment, while in an even smaller physical space. No significant positive result could tell us more about the role of audio in perception building and could spark more research into why, such as studies into how the human brain weighs different senses when establishing perception.

Freely navigating virtual environments contributes to the sensation of feeling present in this virtual environment. This adds to the level of immersion. With locomotion being such a fundamental aspect of immersive experiences, researching natural navigation is key to developing immersive experiences.

II. RELATED WORKS

This study touches upon multiple topics. These topics are listed in the following sections with an explanation of the concept and relevant recent advancements.

A. Human Perception

1) The senses and the vestibular system: Human perception relies on input from multiple senses. Out of the human senses, the vestibular, visual and auditory cues are the primary senses used to support the brain to orient the body [Dichgans and Brandt 1978]. The inputs of these senses are combined with input from the vestibular system. Signals from the proprioceptive system are also integrated with this information into the central nervous system to complete the perception of the body position and orientation in space [Dizio and James R. Lackner 1986].

2) Establishing perception: The brain builds a version of reality by combining all inputs from the different senses with weights assigned to the senses [Clark and Yuille 1990]. These weights are assigned based on the signal's relative reliability [Gao et al. 2020]. After which the perception of the surrounding objects is constructed. This process is known as the maximum likelihood estimation (MLE) [Gao et al. 2020]. Visual cues are most dominant in orienting oneself in space [Pick et al. 1969], [Posner et al. 1976]. By manipulating the most dominant visual signals through RDW, perception can be shifted [Goldstein 1980]

3) Motion perception: The perceptual system distinguishes two types of motion, the user's movements; self-motion, and external motion [James R Lackner 1977]. The judgment of this distinction can be flawed when for example external motion is perceived as self-motion. The chance of this happening increases when more senses support this illusion [James R Lackner 1977]. In response to the illusion of self-motion, the body can produce unconscious self-motion to compensate for the illusion and maintain a consistent perception of space, which forms the basis of RDW. Combined with the studied inaccuracy of estimating distances when multi-sensory input is integrated [Campos et al. 2012], a margin is found in which human orientation and navigation can be manipulated and compensated for, while unaware. As Gao et al. states:

> ”Because redirected walking is based on the human perceptual characteristic of integrating incongruent sensory cues, it could be considered as a perceptual phenomenon when the manipulation is under the detection threshold” [Gao et al. 2020].

B. Locomotion in VR

1) The concept: Types of navigation in a virtual environment can be split into passive navigation, using a controller, or active navigation, where the physical movement of the body is used to navigate the virtual environment [Usoh et al. 1999]. The common techniques for navigating virtual environments are discussed below.

2) Controller based locomotion: The standard use of a controller to rotate and move around is not optimal for use in VR. Moving and rotating in VR without moving your actual body produces vection [James R Lackner 1977]. This is the illusion of moving while standing still, which sends conflicting signals to the brain and causes nausea.

3) Teleportation: Instantly teleporting the user to a location pointed out in the scene, reduces the nausea effects that are experienced with controller-based locomotion. However, the flashes of moving to a new location cause the user to have to adapt to the new location after every teleportation. The use of these techniques can be effective and applicable for locomotion, however, real walking additionally enhances the sense of presence and improves spatial knowledge [Usoh et al. 1999], [Monteiro et al. 2018].

4) Hardware: Hardware solutions exist to keep the user in a fixed place such as an omnidirectional treadmill [Bouguila et al. 2002] and other devices to prevent displacement in the real world such as robot tiles, motion foot pads, and motion carpets [Bouguila et al. 2002]. These devices are considered forms of walk-in place techniques (WIP), which fulfil the function of locomotion, but are found to show less performance on specific factors when compared to real walking [Rietzler, Deubzer, et al. 2020], especially when it comes to navigational search tasks and spatial memory[Ruddle and Lessels 2006]. Even though all these devices can allow for great experiences, however, these solutions also have limitations such as high costs, a set-up process, and the time users need to familiarise themselves with the system.

C. Redirection Techniques

1) The concept: Walking through a virtual environment in the same way as humans do in a real physical environment is the closest way to naturally navigating a 3D environment [Usoh et al. 1999]. However, experiencing a fully virtual environment requires the virtual scene to match the physical environment. This is problematic since the physical world can limit movement in the virtual environment. Compressing the virtual environment into the available physical space could solve this. Redirected walking is one of the techniques to do so. By varying the degrees to which movement in the physical world is translated into movement in the virtual world, the orientation of the user can be manipulated. This allows for the illusion of navigating virtual environments that are larger than the physical space.

Redirected walking techniques can introduce different types of transformation manipulations [Nilsson, T. Peck, et al. 2018]. Each manipulation type utilizes a characteristic of human perception to subtly stretch or shrink the perception of the virtual environment. Suma et al. have developed an extensive framework for all types of redirection techniques. Their paper identifies 3 binary variables, overt vs. subtle, discrete vs. continuous, and a reorientation vs repositioning technique. This framework is shown in Figure 1. [E. A. Suma et al. 2012].

2) Translation gains: The translation gain, sometimes referred to as velocity gain, sets the scale for the user's movement in the virtual world. With a scale of 1:2, moving in a direction in the physical space translates to moving twice as far in the same direction in the virtual environment [Rietzler, Gugenheimer, et al. 2018].

3) Rotation gains: The rotation gain makes use of the disorientation of the user when rotating in a virtual world. The mapping between the degrees of rotation in the real world and the physical world can be altered by increasing or decreasing the degrees of rotation in the virtual environment [Nilsson, T. Peck, et al. 2018].

4) Curvature gains: The curvature gain adds a variable level of continuous rotation while the user is moving forward, resulting in a difference between the perceived walking direction and actual walking direction in the physical world. When applied for an extended time, this allows users to walk infinitely along a virtual path while walking circles in the physical world [Nilsson, T. Peck, et al. 2018], as shown in the paper by [Frank Steinicke et al. 2008] and [Razzaque et al. 2001]. The curvature gain is categorised as a subtle continuous reorientation technique, meaning an imperceptible gain that is dynamically applying a continuous rotation while the user is moving forward [E. A. Suma et al. 2012].

5) Bending gains: Bending gains are a variation of the curvature gains technique where the virtual path is not straight but curved and the continuous rotation while moving along this curved path is still applied. These are described by Rietzler et al. as a relation between real and virtual radius [Rietzler, Gugenheimer, et al. 2018].

6) Other: From the taxonomy laid out by Suma et al. we find more types of redirection techniques are possible [E. A. Suma et al. 2012]. These have also been found to be tested in previous works. In the 'overt' section we find the previously discussed teleportation techniques, the rotation gain with the addition of interventions and the freeze-and-turn technique, where users manually pause the experience to return to a point in the real environment. In the 'subtle' section we find, besides the curvature gain, the previously discussed translation gain, and rotation gain, as well as another technique based on different characteristics of change blindness. An example is the application of dynamic environments, where locations of for example virtual objects such as doors are placed based on the player's location in the real world [E. A. Suma et al. 2012].

Other studies go beyond these techniques identified by Suma et al.. Another studied technique is a prediction algorithm, where gains are applied based on the direction the user is predicted to be moving in the real environment [Fan et al. 2022]. Previous research has also looked into placing distractions in the virtual environment to distract users from the manipulation [T. C. Peck et al. 2011] and by [Rewkowski et al. 2019]. All these techniques can be applied or combined based on the application's needs. An application where multiple factors are successfully combined into a locomotion method is the Telewalk by Rietzler et al. where curvature translation gains are combined and dynamically scaled based on the users' velocity, the available physical space, and the optimal direction the user should go [Rietzler, Deubzer, et al. 2020]. Another example is a technique where multiple users experience RDW in the same physical space, and the RDW technique is adaptive based on the other users' locations [Bachmann et al. 2019]. In the scope of this current research, the curvature gain technique will be discussed and tested. The other techniques are outside the scope of this study.

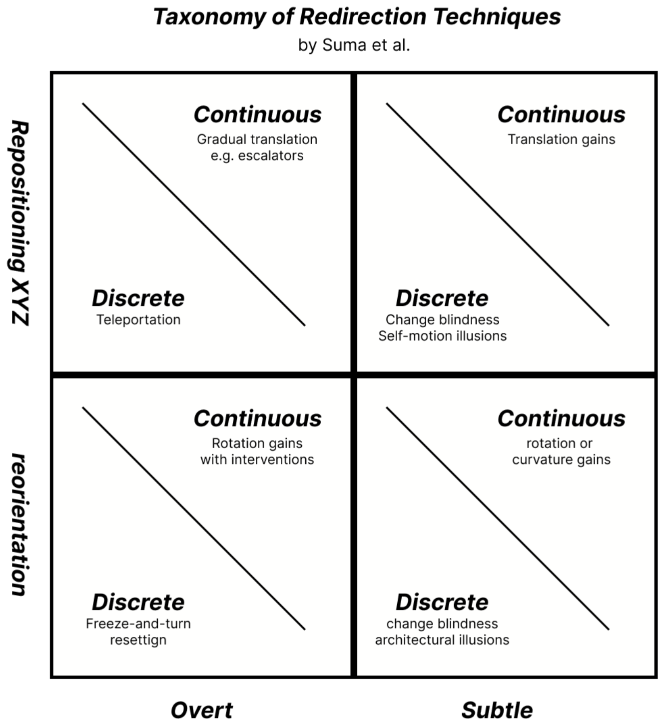

Fig. 1. Taxonomy of Redirection Techniques by Suma et al. [E. A. Suma et al. 2012]

D. Measuring gains and gain uniformity

When researching the perception of each applied gain, it is important to be able to compare the findings to those of other papers, as different papers use different formats to describe applied gain strength. From the radius in meters of the complete walked circle, a degree per 5 meters, to a mathematical expression or expressed as degrees per meter. Rietzler et al. argue that only stating the radius as a measure of the applied gain, is not sufficient to properly compare gains [Rietzler, Gugenheimer, et al. 2018]. This is because the radii scale is not linear in relation to the manipulation as shown in Figure 2.

A small change in applied curvature in degrees per meter can result in a significant shift in the circle's radius. For example, changing the gain 5 degrees from 2°/m to 7°/m results in a diameter shift from 57,3m to 16,37m while the same 5-degree shift from 15°/m to 20°/m results in a shift from 7,64m to 5,73m. This skews the perception and comparability when applying curvature gains. Therefore radii are useful to illustrate the effect of an applied gain, but not appropriate for comparing gains.

To be properly able to do so, Rietzler explicitly encourages further reports on curvature gains for RDW to state both the found radii and gains expressed as x°/m, to allow for a comparison with other findings [Rietzler, Gugenheimer, et al. 2018]. This notation describes the angle per walked meter (x°/m), which in practice means that when the user has moved forward 1 meter, the user will be rotated by x degrees. Additionally, this metric scales linearly with the perceived manipulation [Rietzler, Gugenheimer, et al. 2018].

Therefore this research also uses both radius and x°/m expressions to express the applied gain.

E. Thresholds

The previously mentioned manipulations can be applied at different levels. From not manipulating the translation between the physical and virtual movement, to a strong manipulation [Tan et al. 2022]. The thresholds are expressed in °/m and are found at a different place on the manipulation spectrum for each manipulation technique. Still, as the curvature gain will be used in this research, this manipulation type is studied further. A multitude of studies have been undertaken to explore the detection thresholds of the curvature gain, and test the effects on users under various conditions [Rietzler, Gugenheimer, et al. 2018].

1) Detection thresholds: Nilsson et al. [Nilsson, T. Peck, et al. 2018] state that a translation manipulation needs to be unnoticeable in order to be successfully applied. This points to the first threshold; the detection threshold. The detection threshold marks the manipulation level at which the user becomes aware of the manipulation. With a manipulation bigger than this, the user will detect discrepancies which will break the illusion and weaken the immersion.

For the different RDW techniques, the detection thresholds differ but since this research covers experiments with curvature gains, these will be discussed here.

Previous research from Steinicke et al. [F. Steinicke et al. 2010] has found that 2.6°/m is the detection threshold for curvature gains while Grechkin et al. [Grechkin et al. 2016] state 4.9°/m as the limit for when users detect the applied gain. A similar threshold of 5.2°/m was found by Rietzler et al. [Rietzler, Gugenheimer, et al. 2018], which are shown in Figure 2. When converting these numbers to the needed physical space to complete a full circle, and with that infinite walking, these thresholds require a diameter of 44m and 22m respectively. These are the most frequently mentioned detection thresholds in research, even though in the meantime, albeit under slight changes in methodology, population or conditions, detection thresholds from 2.06°/m [Serafin et al. 2013] to up to 9.48°/m [Meyer et al. 2016] have been found.

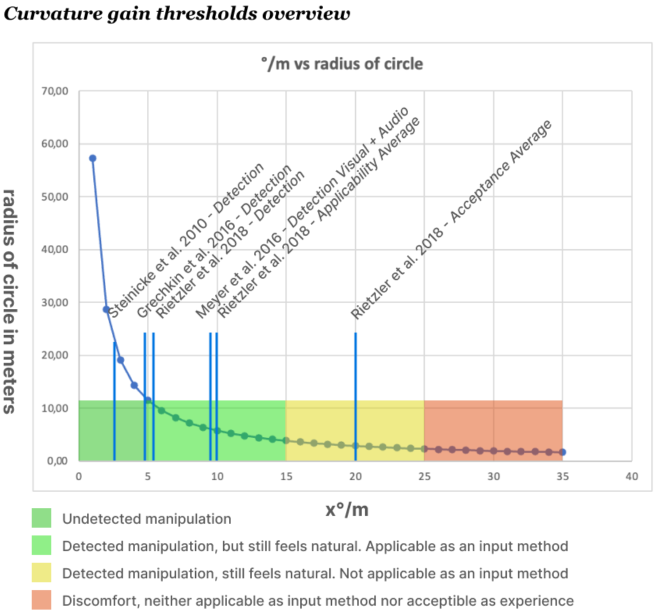

Fig. 2. x°/m vs radius of a circle with the plotted thresholds by Steinicke et al. [F. Steinicke et al. 2010], Grechkin et al. [Grechkin et al. 2016], Rietzler et al. [Rietzler, Gugenheimer, et al. 2018] and Meyer et al. [Meyer et al. 2016].

2) Applicability and Acceptability thresholds: The detection threshold marks the level at which the user first becomes aware of the manipulation, but Rietzler et al. also mention other thresholds. When experimenting with gains above previously researched thresholds, participants were questioned on perceived naturalness and any perceived discomfort. These experiments have led to Rietzler et al. describing the applicability threshold: the level at which the manipulation can no longer be successfully applied as a locomotion technique. Additionally, the acceptability threshold is described as the level at which the user experiences unpleasant side effects caused by the manipulation [Rietzler, Gugenheimer, et al. 2018]. This applicability threshold was found to be around 20°/m, which can roughly be up to 4 times the detection threshold found in a rerun of Langbehn et al. [Langbehn et al. 2017] of 5.2°/m, which can significantly decrease the needed physical space [Rietzler, Gugenheimer, et al. 2018]. The exact thresholds for applicability and acceptability have not been studied extensively by others, mainly due to the belief that gains beyond the detection thresholds can not be applied to RDW.

F. 3D Audio

1) The concept: Spatial audio is the umbrella term for the application of audio elements, spatialized in three dimensions. With that, spatial audio is a technique which adds spatial properties to an audio source to create an immersive experience. Binaural rendering, the head-related transfer function, information on the location of the user, the audio source, and environmental elements are taken into account to process sounds to include spatial elements [Zhang et al. 2017].

As previously discussed, the human perception of audio elements helps to build an environmental representation and to interpret sounds [Kolarik et al. 2015]. The role audio plays in the maximum likelihood estimation is significant [Gao et al. 2020]. Because of these properties, accurate spatial audio experiences have been integrated into consumer experiences and products such as games, and VR products [Zhang et al. 2017].

The effect of adding these spatialized audio elements on the perception of RDW is the main topic of this research. This will determine if spatial audio can strengthen the RDW illusion.

2) Spatial audio applied to RDW - The research gap: Other research efforts have also examined the effect of audio elements in combination with RDW techniques to different extents and under multiple conditions.

Very early RDW research by Razzaque et al. [Razzaque et al. 2001] started experimenting with audio as part of one of the first RDW experiment set-ups to explore if it is possible at all to successfully manipulate a participant's path using RDW, which it did. However, no measurements of detection thresholds were taken here. In this work, Razzaque et al. included spatialised audio as part of the immersive environment.

An RDW study by Feigl et al. has explored the possibility of unknowingly changing orientation perception with only audio cues. Here participants were instructed to walk a straight line in an audio-only VR environment. There was one audio source in the environment which acted as an orientation marker. When this audio source dynamically shifted in the virtual environment, the participants' trajectories shifted accordingly, which shows that users can be manipulated using acoustic signals [Feigl et al. 2017]. While the results are promising, the paper by Feigl et al. has only tested audio for RDW, not in combination with visuals, which the current research is aimed at.

The roles of the different senses when integrating visual cues and audio cues into one congruent perception of the environment is further explored by Gao et al. [Gao et al. 2020]. When presenting the participants with a visually and auditory congruent RDW environment, visual noise, in this case mist, is added to study the shift to the reliance on audio cues. This study finds that the contribution ratio of auditory cues increases as visual noise increases, so when the reliability of the visual stimuli are reduced. Then the effect of incongruent visual and auditory cues on curvature gains was tested. Here it was found that when auditory and visual cues are incongruent, the detection threshold to manipulation of the curvature gain is higher (5.87°/m) and with that, the needed radius of an imperceptible walking circle is smaller (9.8 m) [Gao et al. 2020].

A related study has been conducted by Junker et al. in 2021, with renowned co-author Nilsson on the effects of spatialized sound on detection thresholds [Junker et al. 2021]. Here varying degrees of visibility in the virtual environment with simulated fog were used to test the reliance on the different senses. The experiment set-up was testing rotation gains only. This study was not able to detect effects of spatial audio or changing visibility levels on detection thresholds. This conclusion, when compared to Gao et al.'s conclusion of the possibility of an effect, opens the door again to a further investigation of the topic [Gao et al. 2020].

The conclusion of Junker et al. [Junker et al. 2021] also supports a study by Nilsson et al. [Nilsson, T. Peck, et al. 2018]. Here, no significant difference in detectability between conditions with and without audio could be found. This leads to the hypothesis by Nilsson et al. that the results indicate that the relative influence of audio is minimal because vision is very likely to dominate audition when it comes to the estimation of spatial localisation in a virtual environment. However, this again concerns research into rotation gains, which may lead to different results than curvature gains.

It also must be noted that this research included a condition with static audio, which some participants stated to have reduced their perceived reliability on the audio elements, as it behaved inconsistently due to the randomised order of the audio conditions [Nilsson, E. Suma, et al. 2016]

In 2016, research by Meyer et al. did look into the effects of spatialised auditive elements added to visual elements on the detection thresholds for curvature gains. Here the combined condition of visual and audio elements was tested against only audio elements.

Contrary to their stated hypothesis, the condition with combined audio and visual feedback was found to have a detection threshold of 9.5°/m, which was lower than the audio-only threshold of 16°/m. This result is surprisingly high and could show potential for the addition of spatial audio to raise the detection threshold.

However, a study by Serafin [Serafin et al. 2013] found a detection threshold as low as 3.6°/m for an audio-only condition. This wide variety in results may suggest that there are more factors to be considered and implies that further research is needed. Then there is also the hardware difference where studies such as the one by Serafin provided spatial audio to the participants through 16 physical speakers at the edge of the experiment space, which may lead to different outcomes than when headphones are used to provide the audio in the experiment. It may also be worth noting that many participants from the study by Meyer et al. reported simulator sickness [Meyer et al. 2016].

When comparing Meyer et al. to Gao et al., the found 9.5°/m threshold with audio and visuals combined was also higher than the found 2.6°/m threshold in a no-noise condition with congruent audio and visuals in the study by Gao et al., which resembles the 2.6°/m established by Steinicke et al.

[F. Steinicke et al. 2010]. This may partially be attributed to the difference in the method used to establish spatial audio. Where Meyer et al. used a wave field synthesis (WFS) system and Gao et al. used the head-related transfer function (HRTF). Furthermore, Gao et al. note a difference in the method of plotting the psychometric function when compared to Meyer et al.. This different method makes it difficult to objectively compare the results and the following conclusions.

Research by Weller et al. [Weller et al. 2022] into the addition of audio elements to achieve path manipulation by changing step noises proved to be successful, however, this research was limited to translation gain manipulation.

When combining all these research efforts, a case can be made for both a significant as well as an insignificant effect of the addition of spatialised audio elements. Due to these inconsistencies, further research is necessary to measure the exact effect spatial audio has on the detection thresholds for curvature gains.

III. Research motivation

Drawing from the conclusion of the research gap described above, this research aims to find the answers to the open questions above using the unified method to allow for comparability, which is described in detail in the methodology section.

A. *Aims of the research and hypothesis*

Applying a curvature gain as RDW technique has been proven to be a successful method to reduce the necessary physical space while maintaining the perceived feeling of roaming freely in a virtual environment. However, the required space to achieve a convincing illusion of free-roaming without the manipulation being detected is still large and in most cases too large to fit in a regular living room.

Therefore this research aims to test if the addition of spatialised audio elements, when congruent with visual cues, helps to enrich the RDW illusion and with that contributes to higher detection thresholds for curvature gains. With the previously described integration of multiple senses (MLE) [Gao et al. 2020], each contributing to spatial perception, it is hypothesized that an additional sense confirming the RDW illusion could raise the detection threshold.

This hypothesis has been mentioned before in papers as far back as 1977 in research by Lackner on linear sensory convergence models, which shows that neural inputs are combined to form perception and that when these cues are consistent, human orientation perception can be successfully manipulated [James R Lackner 1977].

The hypothesis from this research is also noted in work by Razzaque et al. in the early 2000s [Razzaque et al. 2001], where the findings by Lackner et al. are once again described by stating that rotation is more likely to be interpreted as self-motion when auditory and visual cues are consistent. This was the motivation for Razzaque et al. to include 3D auditory cues in the first RDW experiments.

This leaves the question of what the effects are on detection thresholds for RDW when these congruent cues are presented to a participant, and in this research specifically for detection thresholds of curvature gains. Therefore this research will try to answer the question if the hypothesized consistency in a set of various cues will increase the detection threshold. The outcomes of the conducted experiments are then compared to other studies on thresholds of curvature gains with only visual cues.

As described in the research gap section, Meyer et al. [Meyer et al. 2016] already studied the hypothesis by Lackner, and the lacking methodology to allow for an equal comparison of the results to other work. In order to enrich the work by Meyer et al. this research will include a methodology comparable to most papers on RDW such as Gao [Gao et al. 2020] and Steinicke [F. Steinicke et al. 2010].

Answering the main research question could also lead to more knowledge on how the human brain integrates sensory information or convergence of sensory inputs as described by Price et al. [Price 2008].

IV. Methodology

A. *Data collection*

The data for this study is gathered through in-person experiments with participants experiencing a virtual environment in which they can roam free within a virtual industrial hangar, built in Unity.

Two identical Meta Quest 2 headsets are used as standalone head-mounted displays (HMDs) running the virtual experiment environment. The tracking, as well as the data collection, is handled by the internal headset sensors.

Since the aim of the research is to measure the effect of multiple conditions on the detection threshold of an applied curvature gain in a redirected walking application, the experiment is set up to measure detection thresholds.

B. *Two-alternative forced choice (2AFC)*

The detectability of the curvature manipulation is tested using a two-alternative forced-choice (2AFC) setup. This method is adopted from related research papers examining detection thresholds in VR such as [Junker et al. 2021], [Gao et al. 2020] and [F. Steinicke et al. 2010] and as a research method for signal detection. Doing so allows for close comparability between papers and eliminates discrepancies in the outcome which could be caused by a differing experiment set-up.

The 2AFC method is implemented as follows. The question posed at the end of each individual trial forces the participant to indicate if the path they walked in the real world was skewed to the left or the right from their virtual path. Comparing these answers, to the real direction of their manipulation results in a percentage of correct answers for each applied curvature gain. These percentages are plotted to compare and draw conclusions.

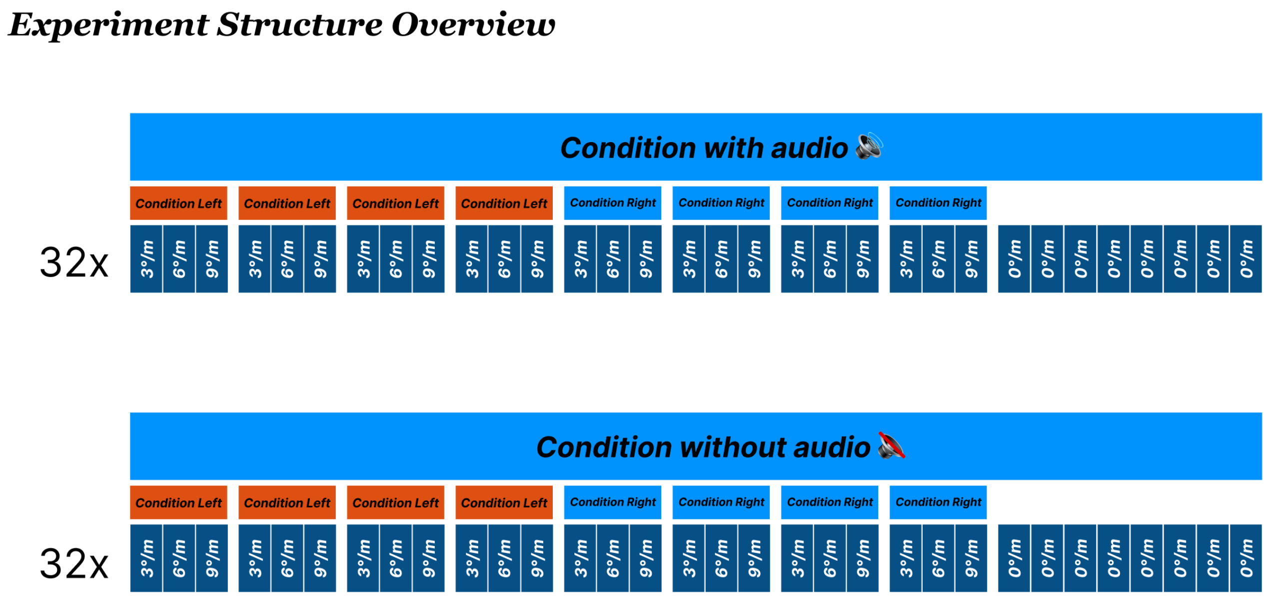

Fig. 3. Overview of the experiment structure

C. Study Design

The study is set up as a within-subjects study based on a 2x4 factorial design, where 2 audio conditions (no audio and spatialised audio) and 4 different degrees of curvature gain (G) being 0°/m, 3°/m, 6°/m and 9°/m, are cross-tested. In all trials, the visual and auditory cues are congruent, with the 4 curvature gains being tested 8 times with audio (4 times to the left and 4 times to the right) and 8 times without audio, resulting in a total number of 64 trials. All participants completed 64 trials spanning all the different conditions being served to them randomly by the experiment engine.

The initiative to contact Dr. Rietzler as a leading expert in the field, and to set up a meeting to discuss the proposed study design, has led to a conversation on the role of chance in the 2AFC set-up of an experiment. Having each condition tested 8 times is advised by Dr. Rietzler. Due to the nature of a two-alternative forced choice (2AFC) experiment, in a lower number of repetitions, the influence of chance could distort the outcome and lead to wrong conclusions. Therefore, the design is adapted to reduce the influence of chance and increase reliability. A visual overview of this structure is shown in Figure 3.

The trials also include a 0°/m condition (where $G = 0/m$) with no manipulation, as a control condition where external factors or biases can be checked, as this condition should roughly have an equal 50% distribution of answers to both the left and right.

The conditions are marked as follows; no audio: A_0 and with audio: A_1.

The different conditions of applied curvature gains are marked G_0, G_3, G_6, and G_9, where each condition applies an increased curvature gain at an interval of 3°/m per condition.

D. The experiment set-up

1) Participants: The participants in this research were selected using convenience sampling resulting in a majority of students from Utrecht University. A total of 18 participants took part in this research of whom 14 identified as male and 4 as female, with a median age of 26 (range = 22 - 28, mean = 25.33, standard deviation (SD) = 1.6).

Each participant was asked to rate the amount of experience they had with VR on a Likert scale from 1 to 7, with 1 being no experience at all and 7 being very experienced. This population was relatively inexperienced with VR as the median rate of experience with VR was 2 with an average of 2.61.

2) Virtual experiment environment: The participants were spawned into the virtual environment where the experiments were carried out. The decision was made to use a vast industrial hangar as a test environment. This was done to provide a realistic and giant environment to explore and roam freely, without the limitations of developing an extensive open world, where mistakes in minor details could quickly reduce the sense of realism. Additionally, the 'sources' of the virtual sounds could be placed outside the hangar while still being realistic to the participant.

A marker was placed on the virtual environment's floor, marking each trial's starting point. A black virtual ball would levitate 4m in front of the spawning position of the participant. This marks the virtual goal to navigate towards. Audio elements were placed on the horizontal plane which surrounded the user in all 360 degrees. The Oculus Spatializer applied

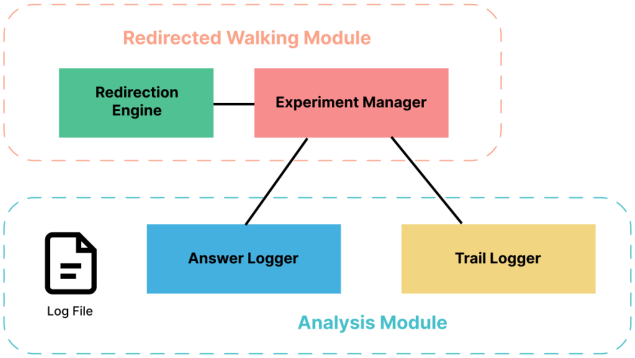

Fig. 4. Schematic overview of the code structure.

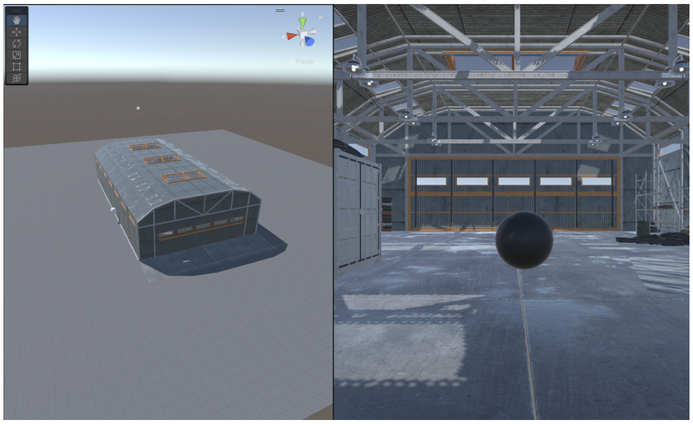

Fig. 5. Screenshots from the virtual experiment environment taken from Unity with on the left the exterior of the experiment environment and on the right side the viewpoint of the participants when being spawned into the environment. The floating black orb is the goal.

spatial properties to the two-channel audio system which led to the headphones worn by the participants. The spatialised sounds were played from 3 sources. On the right side, outside the hangar, a street soundscape is placed. On the left side outside the hangar, a collection of sounds from industrial machinery was placed. The goal marker emitted a pulsating sound itself. Each trial consisted of walking from the start marker to the goal.

3) Code Implementation: The C# code to run the experiment consists of 4 components as shown in Figure 4. The experiment manager, redirection engine, trail logger, and answer logger. The experiment manager loads the scenes in the right order, the starting scene, the training scene and the main experiment scene. This module also toggles the audio on and off. Within the main scene, the trials are loaded randomly from a list of all trials and then marked as completed. Each trial loaded by the experiment manager contains one of the possible curvature gain strengths, a direction to the left or right, as well as a setting for audio being on or off. When loading a new trial, the experiment manager applies this manipulation to the Unity environment. This code applies a rotation to the complete environment when the participant is moving forward on the z-axis in the real world, resulting in a proportional rotation. The redirection engine is calibrated by analysing the logs of the walked paths for each applied curvature gain multiple times in the development phase and by placing markers in the real-world environment at the measured curves, resulting in a calibrated experiment set-up.

The coordinates of the paths walked by the participants from the starting point to the goal are tracked by the trail logger method to later be plotted. After each trial, the provided answers are logged by the answer logger and added to the log file. The implementation uses custom C# code and Unity version 2021.3.11f1. The installed packages to enable the VR experience are the XR Interaction Toolkit by Unity, Oculus XR Plugin version 3.0.2 to support the Meta Quest 2 device, and the Open XR Plugin version 1.4.2. The spatial audio is managed by the Oculus Spatializer plugin. The used hardware were two identical Meta Quest 2 headsets, both set at the default refresh rate of 72hz. Two devices were used to allow for continuous testing, while the other device was charging. The Bose QuietComfort 25 noise-cancelling headphones are used to provide the spatial audio elements and immerse the participants in the virtual world, as external sounds such as cars, birds and sirens are blocked.

As the Quest 2 as a standalone device fully relies on visual tracking by selecting markers in the real-world environment and triangulating distance to these points to calculate the location, this system was helped by placing high contrast reference markers, printed on A4 paper, in the physical environment. When testing, this addition improved the ability of the HMD to track the location and avoid glitches during the experiment.

4) Pre-test phase: In the process of registering as a participant on a web form, before experiments take place, the potential participants were instructed on the purpose and procedures

Fig. 6. A first-person view of the training scene where the participants familiarise themselves with VR and the functionalities of the VR experiment.

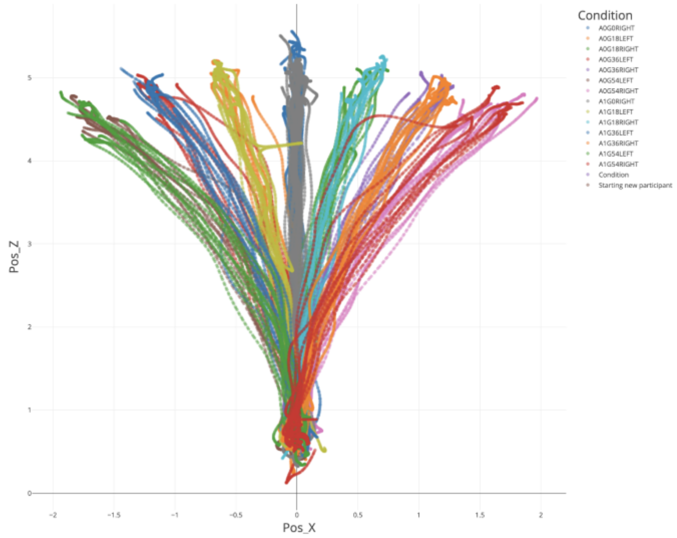

Fig. 7. Top-down view of the physical experiment environment with the paths walked by different participants at different curvature gains. The different colours indicate each differing condition, with and without audio.

of the experiment. They confirmed having the ability to walk around for the duration of the experiment and confirm having normal or corrected to normal vision and hearing. There was also the opportunity to contact the researcher for questions.

5) Test phase: The experiment consists of an introduction, where the researcher asks if anything has changed between signing up online and the date of the experiment. Here the participant also gives written consent to take part in the experiment. The experiment can be paused or ended at any moment if the participant wishes to do so and there is room for questions.

The experiments are carried out in a physical space with a virtual boundary of 5m by 5m, at a Utrecht University space. After entering the tracking area, the participant is fitted with the HMD and both controllers, before being instructed on the use of the HMD and controller in the virtual environment.

The experiment includes an introduction scene where the participant can familiarise themselves with VR, the headset, controllers, buttons, and the virtual environment.

Here they could walk around and walk without any manipulations to the mapping. After familiarising themselves with the environment, the experiment was started.

6) Procedure: Each individual trial consists of the following steps:

1) Participants are instructed to walk in a straight line for 4m to the black target ball.
2) With each movement forward, the randomly selected manipulation of curvature gain is applied.
3) When reaching the ball, the manipulation is paused and the 2AFC question field is spawned with two buttons for the options.

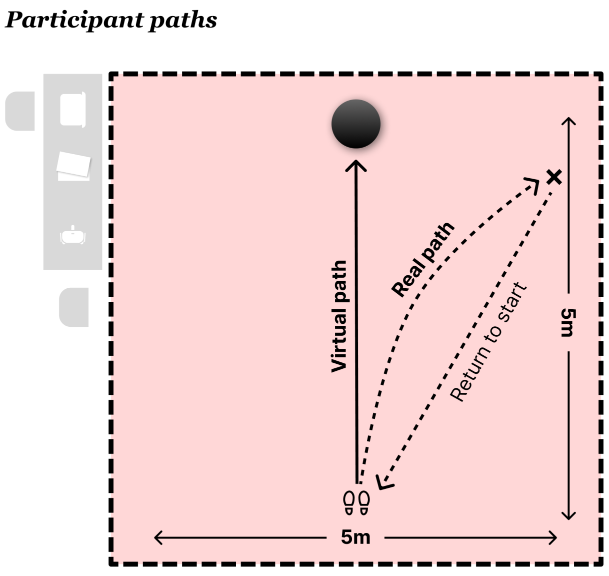

Fig. 8. Top-down view of the physical experiment environment with the paths indicated in the physical world as dotted lines, and in the virtual world as solid lines

4) The 2AFC question is answered by selecting the button ’Right’ or ’Left’ with the trigger on either controller.
5) The participants navigate to the start marker.
6) A field has appeared with a button to start the next trial.
7) The participants select the ’Next’ button to start the next trial

E. Statistical analysis of the results

From this experiment, data is collected on the perception of the curvature manipulation of the virtual environment. First, the answers to the perceived manipulation direction are collected, secondly, the coordinates of the walked paths are recorded to observe if the manipulations are successfully applied, and finally, basic data on the population sample is collected.

The data of the provided answers to each trial are converted to a correctness percentage and then plotted as a psychometric function, from which the detection thresholds are derived by determining a point of subjective equality (PSE) where participants can correctly determine, beyond chance, if their real-world path is manipulated to the left or right. The points at which participants correctly respond to the 2AFC question in 75% of the trials is considered to be the detection threshold as this is standard practice in papers on the same topic [Junker et al. 2021] and [F. Steinicke et al. 2010].

To fit the data into a psychometric function, Python was used. The existing package FitPsyche was used to plot the symmetrically structured data of ’percentages correct’ of both conditions with and without audio. The PsychometricCurve function uses two more parameters by Wichmann and Hill

[Wichmann and Hill 2001]. These are the guess rate of 0.5 and a lapse rate of 0.05, where the guess rate indicates the average percentage correct for total random guesses of the 2AFC task. This is 50% since there are 2 alternatives, left or right. The lapse rate introduces a correction for participants' fallibility of an incorrect answer by accident or any other reason beyond the stimulus strength. Including these corrections in the formula improves the estimation of the detection thresholds [Wichmann and Hill 2001].

The dependent variable used is the percentage of correct answers. The independent variables are the applied curvature gain and the presence of audio, being the curvature gains of 3°/m, 6°/m and 9°/m to both the left and right and 0°/m, all of which are tested in conditions with and without audio. This results in a table with the percentage correct per participant and per tested curvature gain for both with and without audio conditions as shown in Table 1

Comparing the percentage of correct answers for the conditions with and without audio gives an indication if there is a difference between how well participants are able to detect a manipulation in both conditions. A higher percentage of correct answers indicates a better ability to detect manipulations. A similar percentage indicates no difference in perception ability leading to the following hypotheses.

H0 = Audio has no significant effect on the % of correct answers
H1 = Audio has a significant effect on the % of correct answers

A two-way repeated measures ANOVA is performed to test for a significant difference in detection threshold between 4 strengths of curvature gain manipulation and the conditions with and without spatial audio elements. Plotting the psychometric function to the data for both conditions allows for a comparison in the PSE values.

V. RESULTS

First, the coordinates of the walked paths, as shown in Figure 7, are plotted and visually analysed. These plotted paths clearly show the effect of the applied curvature gains to both the left and the right. The straight line on the control condition of G_0 with 0°/m also confirms the absence of external factors influencing the redirection such as features in the virtual environment or natural deviations.

The data gathered from the 2AFC task, when grouped per audio condition and per curvature gain, is shown in Table 1. This data is analysed using Python, Numpy, Seaborn, Matplotlib, Pingouin and Pandas. The results are analysed using a two-way repeated measures ANOVA.

	Correct	**SD**	**MOE**	**LL**	**UL**
G_0A_0	45.46%	0.282	± 0.130	0.326	0.589
G_3A_0	65.49%	0.191	± 0.088	0.564	0.741
G_6A_0	76.06%	0.271	± 0.125	0.636	0.886
G_9A_0	81.25%	0.239	± 0.111	0.702	0.923
G_0A_1	45.77%	0.216	± 0.099	0.354	0.553
G_3A_1	58.45%	0.218	± 0.101	0.483	0.685
G_6A_1	65.73%	0.270	± 0.125	0.531	0.781
G_9A_1	78.62%	0.264	± 0.122	0.663	0.907

TABLE I
THE PERCENTAGES OF CORRECT ANSWERS PER CONDITION. THE CONDITIONS, LISTED IN THE COLUMN ON THE FAR LEFT, USE THE G TO INDICATE THE APPLIED CURVATURE GAIN AND THE A FOR THE APPLIED AUDIO CONDITION WITH A_1 MARKING A CONDITION WITH SPATIAL AUDIO. NOTE: FOR THE G_0 CONDITIONS OF 0°/M, THE PERCENTAGE SHOWS THE PERCENTAGE OF ANSWERS INDICATING A MANIPULATION TO THE RIGHT, AS THERE IS NO RIGHT OR WRONG ANSWER, BUT THE DISTRIBUTION CAN BE AN INDICATION OF EXTERNAL FACTORS. THE CONFIDENCE INTERVAL IS SET AT 95% WITH THE CORRESPONDING MARGIN OF ERROR (MOE) AND LOWER (LL) AND UPPER LIMITS (UL) PERCENTAGES EXPRESSED IN DECIMALS.

This revealed a significant main effect and a small effect size of *Audio (F (1, 17) = 8.599, p = 0.0093, partial* η^2 *= 0.011)*, a significant main effect and small effect size of the *Curvature Gain (F(3, 51) = 14.96, p = 0.000025, partial* η^2 *= 0.22)*, and no significant interaction effect *(F (3, 51) = 0.753, p = 0.498, partial* η^2 *= 0.0068)*.

For the purpose of this research, the main effect of the addition of audio is found to be significant which leads to rejecting H0. With that, H1 is supported, meaning the addition of spatial audio significantly affects the detection threshold. The point of subjective equality (PSE), being determined at 75% correct answers on the psychometric function, finds the detection threshold for the conditions without audio at 6.2043°/m. and the detection thresholds for conditions with audio at 8.7829°/m. An interpretation of the detection threshold is the point at which participants are able to determine whether their physical path is skewed to the left or right, at 75% accuracy. Fitting the psychometric function to the experiment data revealed a fit for the A_0 condition with an R^2 of 0.990 and an R^2 of 0.981 for the A_1 condition. This high fit indicates a good fit of the psychometric model to the experiment data and that it is likely to be an appropriate representation of the data. Plotting the data and psychometric functions to the data as shown in Figure 9 shows the fitted curves for both conditions and the corresponding PSE values as described before.

VI. DISCUSSION

The results show a significant impact of the presence of spatial audio elements on the detection threshold.

The percentages of the condition with no applied curvature gain, are very close in both the conditions with and without audio (45.45% and 45.77%) and approximately 50% in the

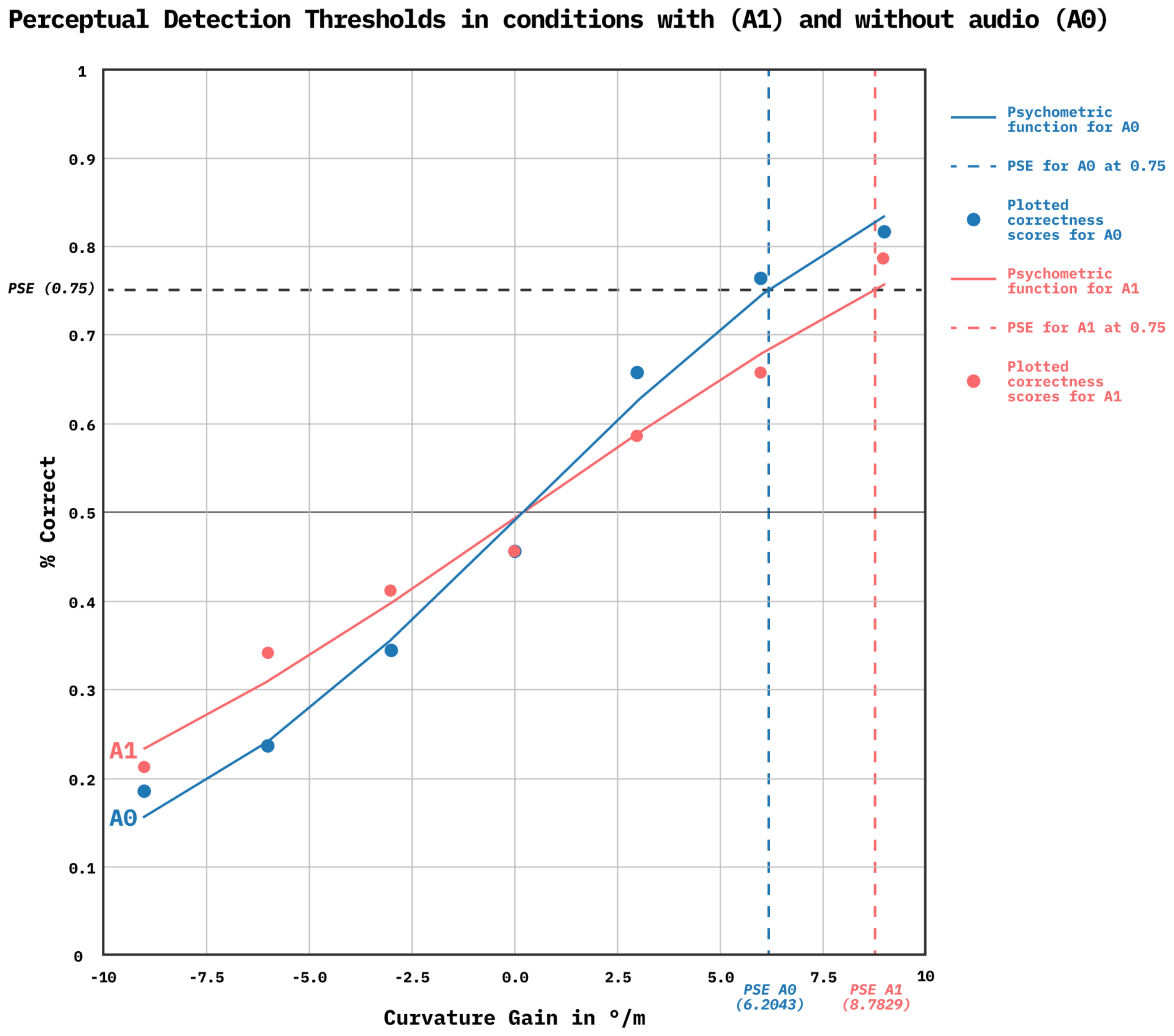

Fig. 9. Results of perceptual detection thresholds for curvature gains in conditions with (A_1) and without audio (A_0) at PSE of 0.75 using a psychometric function with With on the x-axis the signal intensity, in this case, the curvature gain, and on the y-axis the percentage of correct answers.

psychometric plot. While for all curvature gains with audio, the percentage of correct answers is lower, indicating a lower ability of participants to consequently detect the manipulation without a noticeable bias to either side.

As discussed in the related works section, the generally accepted detection threshold for curvature gains as found by Grechkin et al. [Grechkin et al. 2016] is set at 4.9°/m. This is in a situation without congruent audio cues. In the comparable condition of A_0, the psychometric function returns the found detection threshold of 6.2°/m which is slightly higher than expected. The increase in detection threshold of 2.5°/m to 8.7°/m in A_1 shows a relatively big impact of the presence of spatial audio.

Contrary to findings by Junker et al. [Junker et al. 2021] and Nilsson et al. [Nilsson, E. Suma, et al. 2016] on the addition of audio when applied to rotation gain, the addition of audio does show a difference in detection thresholds for curvature gains.

Junker et al. found no significant difference, and follow the hypothesis by Nilsson et al. that the absence of an effect can be attributed to visual dominance. However, in the current research, visual dominance appears to be less likely to have an effect on curvature gains.

During the trials, participants responded that they may notice the manipulation direction by focusing on the weight on a particular part of their feet. Using this method to assess where

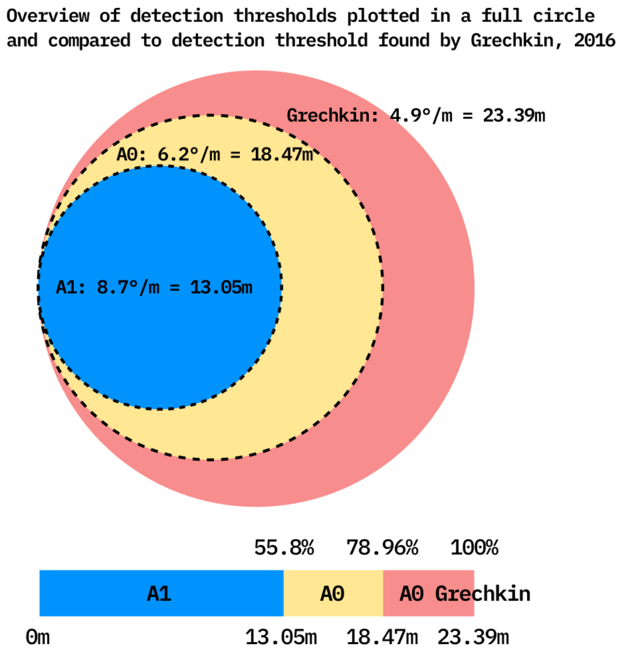

Fig. 10. Overview of detection thresholds plotted in a full circle and compared to the detection threshold found by Grechkin, 2016, showing the implications of needed space for circles at radii of found detection thresholds

they are walking is an interesting way to add information to the sense of orientation and the vestibular system. The outcome of this experiment is not very likely to be influenced by this strategy as this would increase the accuracy of participants in both conditions with and without audio. It could however cause a limitation for experiments with higher curvature gains, as the participants' feet may touch each other and with that break the illusion.

A. *Implications*

The implications of an increase in detection threshold between A_0 and A_1 can be expressed in the minimum required diameter of a circle for an imperceptible curvature manipulation when walking. Without audio (A_0) this diameter is 18.47m. When applying audio, this diameter can be reduced to 13.05m, which is a reduction of 29.34%. in diameter.

When comparing this change in detection threshold to the needed space at the detection threshold found by Grechkin [Grechkin et al. 2016], the potential becomes more apparent. At the threshold of 4.9°/m [Grechkin et al. 2016] a circle with a diameter of 23.39m is required. The difference between this diameter and the diameter at A_1 is a reduction of 44.2% in needed space. This difference is shown in Figure 10. This shows that the required space to achieve a convincing illusion of free-roaming can be significantly decreased when applying spatialised audio elements.

B. *Potential causes*

A cause can be that the spatialised audio elements are used in the maximum likelihood estimation (MLE) in the brain in the same way as natural audio cues and thereby strengthen the created RDW illusion, leading to a more convincing redirection and resulting in lower levels of correct answers. Another possibility is that the presence of audio distracts the user when carrying out the task to walk straight and detect a manipulated path. The added spatialised audio could lead to an increase in cognitive load on the participant and with that lower the ability to detect the direction of the manipulation.
In both these situations, the addition of spatialised audio elements does lead to a higher detection threshold. Other influences of the added audio can also lead to the found results.

VII. LIMITATIONS

Limitations of this research include the sample. As the sample predominantly consists of subjects from the Netherlands, the WEIRD problem applies. With the data being collected from a Western, educated, industrialised, rich and democratic society, generalising the results and conclusions and applying these to other populations may be incorrect. Differences in exposure in Western societies to digital devices may change the susceptibility to manipulations, as well as general abilities to integrate sensory cues. The sample is also limited by age distribution as the sample only includes participants between the ages of 22 and 28. This limits the applicability of the findings for subjects of significantly different ages. Another limitation of the research may also be the specifications of the used hardware. With the Meta Quest 2 devices being set to a refresh rate of 72hz, the effect of this on comparability to previous work at 60hz or studies without a refresh rate indication is not known. As a higher refresh rate may approach a human perception limit, which may increase the sense of presence and other factors which may influence manipulation detection ability. This also applies to other HMD-specific specifications such as varying degrees of field of view (FOV).

VIII. FUTURE WORK

Future work on curvature gains in RDW context can explore the effect of spatial audio elements on dynamics curvature gains, where curvature gains are dynamically applied based on the position of the subject in the physical world. Especially the relation between the strength of the applied curvature gain and the presence of spatial audio can be further investigated.

The subjective perception of curvature gains can also inspire future research on the topic of different personal factors responsible for establishing personal detection thresholds. Calibrating an RDW VR application to operate within the limits of a personalised detection threshold for situations with and without spatial audio can be a next step.

The effect of the hardware specifications as mentioned in the limitations section may also spark future research with hardware yet to be developed.

IX. CONCLUSION

The result of a lower ability to correctly detect manipulations in conditions with spatial audio elements, combined with this result being proven to be significant, suggests that the addition of spatial audio elements leads to a higher detection threshold for curvature gains in RDW of up to 8.7°/m, an increase of 2.5°/m compared to the condition without spatial audio elements. This in turn implies a required circle with a diameter of 13.05m to successfully apply an undetected curvature gain to a RDW VR context.

Further research can be conducted into the cause of this finding to further explore the possibilities of applying spatial audio in RDW and the potential of spatial audio to increase the detection threshold.

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