Impact of Threshold-Relative Curvature Gains on Cognitive Cost: A Pilot Study

Carolin Reichherzer
Lucerne University of Applied Sciences and Arts
Rotkreuz, Switzerland
carolin.reichherzer@hslu.ch

Michelle Meyer
Lucerne University of Applied Sciences and Arts
Rotkreuz, Switzerland
michelle.meyer@hslu.ch

Anh Nguyen
Lucerne University of Applied Sciences and Arts
Rotkreuz, Switzerland
anh.nguyen@hslu.ch

Markus Zank
Lucerne School of Information Technology
Lucerne University of Applied Sciences and Arts
Rotkreuz, Switzerland
markus.zank@hslu.ch

Abstract

Redirected Walking provides a potential approach to enable natural walking in virtual environments in limited spaces, but it may introduce additional cognitive demands. While redirection is intended to remain imperceptible, detection thresholds vary between individuals, and it is unclear how noticeability at these different levels affects cognitive task performance. In this paper, we present a pilot study where we first establish a group-level psychometric curve to extract the detection threshold for curvature gains. We then follow up with a dual task where participants navigated a virtual labyrinth while performing a memory task with gains applied on threshold, above threshold, below threshold, and with no redirection. We found that accuracy significantly decreased and the false alarm rate significantly increased in the under threshold condition compared to baseline. We discuss the implications of these findings and directions for future work.

CCS Concepts

• **Human-centered computing** → **Empirical studies in HCI**; **User studies**; **Virtual reality**.

Keywords

Redirected Walking, Virtual Reality, Cognitive Performance, Detection Thresholds

ACM Reference Format:
Carolin Reichherzer, Michelle Meyer, Anh Nguyen, and Markus Zank. 2026. Impact of Threshold-Relative Curvature Gains on Cognitive Cost: A Pilot Study. In *Extended Abstracts of the 2026 CHI Conference on Human Factors in Computing Systems (CHI EA '26), April 13–17, 2026, Barcelona, Spain.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3772363.3798536

1 Introduction

Redirected Walking (RDW) is a locomotion technique that could provide a solution to enable real walking in Virtual Reality (VR) within limited physical spaces. In RDW, the user is steered through subtle perceptual manipulations in the virtual environment (VE) in an attempt to compress a larger VE into a smaller physical space. RDW has shown promise in offering an alternative to current navigation techniques. For example, a study conducted by Peck et al. [20] found that participants performed significantly better on a wayfinding task using RDW compared to techniques that do not employ redirection. Another study by Langbehn et al. found that RDW and teleportation perform similarly in terms of spatial cognition and were preferred over joystick usage [12].

An important aspect of applying RDW techniques is that the amount of redirection applied should not be noticeable to users. This represents the tolerable amount of deviation between the visual and vestibular systems while the user is manipulated by redirection gains. This tolerable amount of deviation is referred to as the detection threshold (DT). There has been extensive work attempting to quantify these thresholds [15–17, 20, 22]. A further important consideration is that detection thresholds are perceived differently by individuals. Prior work has shown that gender significantly affects DTs, with men tending to be more sensitive than women in detecting curvature [16] and rotational gain [24].

Further, RDW has the potential to increase cognitive load and interfere with spatial memory [18]. Prior work has shown that higher gain levels can significantly decrease verbal and spatial memory performance [2]. However, the effect of redirection on cognitive load remains unclear, particularly when gains are applied relative to users' detection thresholds. For RDW to become a viable alternative to existing navigation techniques, it is necessary to understand whether these manipulations draw on cognitive resources in ways that meaningfully affect performance, and how RDW can be applied to maintain cognitive performance.

To address this gap, we conducted a pilot study where we first computed the psychometric curve of our participant sample to estimate the DT. We then conducted a cognitive task using gains derived from this curve to assess performance below, at, and above threshold, comparing these conditions to a baseline with no redirection.

CHI EA '26, Barcelona, Spain

ACM ISBN 979-8-4007-2281-3/26/04
https://doi.org/10.1145/3772363.3798536

2 Related Work

2.1 Evaluating Detection Thresholds

Users' responses to different stimulus levels are conventionally modeled as a psychometric curve. Variations in detection procedures result in different curves. In a yes/no task, a single non-zero stimulus is presented and the user is asked if they detected it; the threshold is defined as the stimulus level where the user responds "yes" 50% of the time. In a two-alternative forced-choice (2AFC) task, two options are presented, and the threshold is generally defined as the stimulus level at which users answer correctly 75% of the time.

Two main groups of methods exist: the constant stimuli method (CSM) and adaptive methods. CSM involves sampling a set of stimulus values across a range and fitting the responses to a predefined function. Most existing studies on RDW threshold identification employ this method [3, 4, 7, 13, 15, 22, 26]. While CSM is straightforward to implement, it requires a large number of repetition at each stimulus level. Alternatively, adaptive methods such as staircase [5] and Bayesian methods [8, 23] require fewer trials. However, these generally identify only the threshold rather than the entire psychometric curve [7, 9, 10, 16, 17, 21].

2.2 Cognitive Load in RDW

A frequently employed method to measure cognitive load during locomotion is to require the user to perform a secondary task, referred to as the dual-task paradigm [14, 25]. Performance in the dual task serves as an indirect measure of the cognitive load imposed on the user by the primary task [1]. There is limited literature assessing cognitive demands in RDW, and existing studies usually involve tasks performed while walking in a straight line. Bruder et al. conducted a dual-task study where participants performed spatial and verbal memory tasks while walking along a pavement; they found that higher curvature gains significantly decreased performance [2]. A similar study assessed cognitive load with varying curvature gains in two different VEs [14]. In that study, participants followed a path while completing a spatial memory task. While the results did not show a significant effect of curvature gain on cognitive performance, the authors noted that visual inspection suggested a decline in the percentage of accurate responses as gains increased in one of the two VEs.

While there is some indication that RDW may affect cognitive performance, studies to date have not considered how detection thresholds may further contribute to this effect. Additionally, research has primarily focused on assessing cognitive tasks while walking along a straight path. We contribute to existing research by considering the detection threshold of our sample and assessing cognitive performance while navigating a more complex path in a labyrinth.

3 Pilot Study

To assess whether redirection applied below, at, or above the DT affects cognitive load, we conducted a pilot study consisting of two sessions using the same group of participants: 1) a detection task that formed the basis for identifying the DT, and 2) a dual task consisting of an auditory 2-back task to assess cognitive load at previously identified levels of redirection intensity while navigating a labyrinth in a VE.

3.1 Identifying the Detection Threshold

The first session was aimed at identifying the values for the DT, as well as values below and above the threshold at a group level, to form the basis for the cognitive task in the second round. For this experiment, participants walked down a virtual passageway towards a red target twice; in only one walk was a curvature gain applied, while the other trial did not contain redirection. Following the completion of the second walk, they were asked the question: "*In which walking trial did you walk on a curve?*" This allowed the entire psychometric curve to be identified, and multiple points from this curve could then be used for the second part of our study. The range and resolution of curvature gains were selected based on previous work [2, 6, 7, 14, 22]. We utilised a range of $1^\circ/m$ to $6^\circ/m$ with a resolution of $1^\circ/m$, resulting in six curvature gain levels: $g_C \in \{0.018, 0.035, 0.052, 0.070, 0.087, 0.105\}$.

3.2 Dual Task

The gains derived from the DT task formed the basis for the conditions of *"Under Threshold"* (UT), *"On Threshold"* (ON), and *"Over Threshold"* (OT). We further added a baseline condition with *"No Redirection"* (NO) applied.

In this task, participants followed the pathway of a labyrinth while responding to an auditory stream of letters for the 2-back task. There was a 2500 ms gap between letters and the target rate was set to 30%. Participants indicated whether the current letter matched the one presented two items earlier by pressing a button on the remote presenter. Because the tracked physical space was smaller than the virtual walking space, resets were initiated at the border of the tracking space so participants could continue navigating their path. A condition was considered complete when the participants covered a distance of 150 meters.

3.3 Apparatus and Experimental Setup

The software was created using Unity version 6000.0.31f1 and consisted of two parts: one part for the DT task and the second for the dual task. The DT task consisted of a passageway with a red sphere at the end. The gains were randomly assigned to the first or second path and always redirected in a left curve. The second part consisted of a labyrinth layout for the cognitive task. We utilised a steer-to-centre (S2C) redirection algorithm that applied only curvature gains. A prediction algorithm was implemented to initiate resets, but it did not influence the S2C. The prediction was based on the user's trajectory and a NavMesh of the labyrinth. The reset algorithm optimised the participants' facing direction so that the distance to the next corner and the direction of the next corner would best fit the available physical space. During the reset participants needed to stop and spin on the spot. A rotation gain was applied so that the user spun between 360° and 540° depending on their start rotation and the optimised end rotation. A user interface indicated in which direction the user had to turn and until final orientation was reached. We created two labyrinth assets with an equal number of left and right corners. Both labyrinths could be

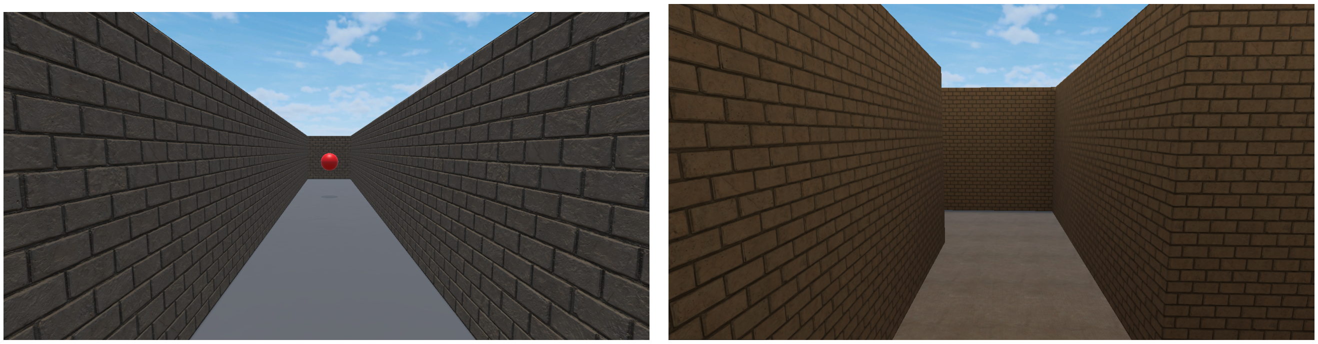

Figure 1: The study consisted of two sessions: walking towards a red target for DT (left) and navigating a labyrinth in the dual task (right).

started from either direction resulting in four path variations. See Fig. 1 for an impression of the DT task and the labyrinth.

A 9m x 6m tracking space was set up in an empty open space. The space including a safety margin was sectioned off with warning tape. The experiments were conducted using an HTC Vive Focus 3 with a refresh rate of 90 Hz. 6 GHz Wi-Fi streaming via Vive Business Streaming ensured cable-free movement through the space. The computer used for streaming was equipped with an Intel Core i7-11700F CPU and an Nvidia RTX 3080 GPU. For the second part, users wore a wired over-ear headset and used a Logitech Spotlight presentation remote.

3.4 Participants

We recruited 21 participants from our University community (12 male, 7 female, 2 non-binary). Participants were aged between 20 and 52 years ($M = 32.4, SD = 11.21$). After completion of the second part of the experiment, participants were awarded 20 CHF as a token of appreciation for their time. As part of the eligibility criteria, participants had to be over the age of 18, be comfortable walking for up to 45 minutes at a time, and have normal or corrected-to-normal vision. Ten participants stated they used VR at least once per month or more, whereas two had never used a VR headset before. Written informed consent was obtained from all participants ahead of their participation. This study was approved by the institutional ethics committee.

3.5 Procedure

The study was conducted in two stages. The goal of the study was to conduct the cognitive task close to the individual DT of participants; however, pilot studies showed that to detect the individual threshold it would require running longer trials to get enough data to calculate each person's individual DT. To keep the study contained, we decided to calculate the DT on the entire sample of participants, and then use the calculated sample to generate the gains for the cognitive tasks. Therefore, participants came in to conduct the DT task, and then completed the second task roughly one week later. All participants returned for the second part of the study.

For the detection task, participants were equipped with the VR headset following an introduction and completing a short survey on demographics. In VR, participants first completed a tutorial to become acquainted with the task. Upon completion of the tutorial, participants completed the main task which consisted of walking down a virtual passageway towards a red target twice, once with and the other without redirection applied. The order in which redirection was applied was random. After a total of 30 trials (6 curvature gains repeated 5 times, counterbalanced in blocks), the session was complete. The entire session took approximately 30 minutes.

The same participants from the detection task stage returned for a second session in which they performed a dual task consisting of the auditory 2-back task while navigating a labyrinth, in four conditions: NO, UT, ON, and OT. For each of the conditions, we recorded correct responses, false alarms, reaction time, completion time, and the number of resets. After completing a tutorial, participants entered the main study where the order of conditions was counterbalanced. At the end of each condition, participants had the opportunity to take a break and drink water. They were further asked to answer a question on perceived cognitive load using the Paas scale [19] and the Cybersickness in VR (CSQ-VR) questionnaire [11]. Throughout the session, the experimenter monitored participants' comfort, and participants had the option to stop at any time. Upon completion of all four conditions, they were asked to fill out an additional open question on their overall experience. This session took approximately an hour.

4 Results

4.1 Group Detection Thresholds

Detection data were pooled across participants to estimate a group-level psychometric function using the R package *quickpsy* (see Fig. 2). We mapped the proportion of correct responses against curvature gain using the cumulative normal function with a guess rate fixed at 0.5. The group DT was defined as 75% correct and resulted in a value of $g_c = 0.0835$ ($4.78°/m$). Based on this model, sub-threshold and supra-threshold curvature gains for the subsequent n-back task were identified as the points corresponding to 62.5% and 87.5% correct: $g_c = 0.0621$ ($3.56°/m$) and $g_c = 0.105$ ($6.02°/m$), respectively. These points were selected as symmetric points around the DT, halfway between guessing and the DT, and between the DT and perfect performance. Goodness-of-fit tests were not significant, therefore indicating that the estimated functions fit the data well.

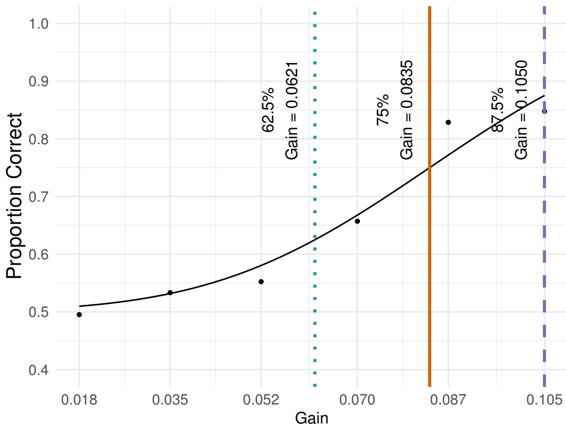

Figure 2: The psychometric curve with the DT (orange), below threshold (green) and over threshold (purple).

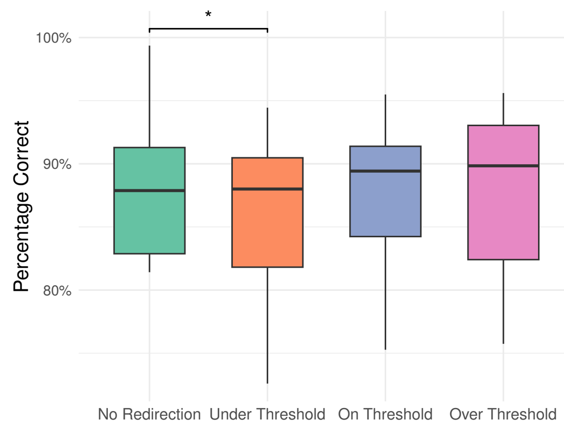

Figure 3: Participants in the UT condition were significantly less accurate compared to baseline during the dual task.

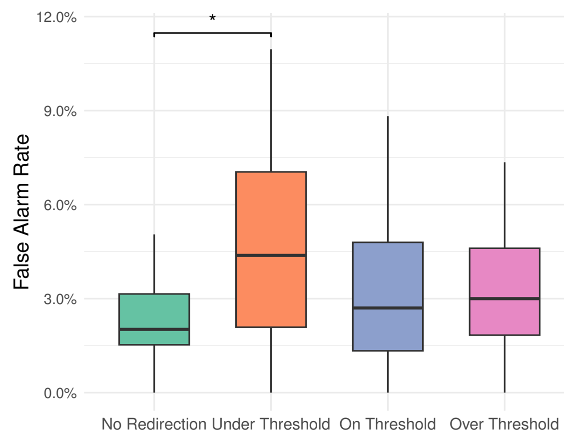

Figure 4: Participants in the UT condition showed a significantly higher false-alarm rate than in the baseline condition.

4.2 Dual Task Performance

Two participants were removed from the dataset. For one participant, we encountered technical difficulties in the network, which led to severe latency issues that could not be resolved during the session. Another participant did not correctly perform the resets and became unwell. Further, plot inspections and influence diagnostics (Cook's $D = 0.30$) indicated one participant was an outlier for the UT condition. Upon closer inspection of the logs, we found they must have accidentally pressed the wrong button for target trials, therefore not registering any matches for target trials in this condition, which was unlike the other conditions for this participant. We therefore removed only this condition for this participant, resulting in 18 data points for the UT condition and 19 for the remaining conditions.

We analysed accuracy for the 2-back task using a binomial GLMM with the logit link function, with condition as a fixed effect and participant as a random effect, modelling the number of correct responses out of the total number of trials per participant and condition. Furthermore, the number of resets and the reset rates differed between conditions and participants. On average, participants completed 16.4 resets in the baseline condition ($SD = 1.54$), 15.7 in ON ($SD = 2.23$), 15.8 in OT ($SD = 2.37$), and 14.5 in UT ($SD = 2.48$). To control for these differences, we included reset rate as a covariate, defined as resets per minute and computed as $60 \cdot \text{resets}/\text{time}$ with time in seconds. Post-hoc comparisons with Bonferroni-Holm correction revealed that only the UT condition significantly reduced accuracy compared to the NO condition ($OR = 1.26, p = 0.042$). See Fig. 3 for results. Reset rate was not a significant predictor of accuracy.

We also modelled hit rate and false-alarm rate using two separate binomial GLMMs. Hit rates did not significantly differ across conditions; however, Bonferroni-Holm-corrected pairwise comparisons indicated a significant difference in false-alarm rate between NO and UT ($p = 0.01$). The estimated false-alarm rate increased from NO (2.45%) to UT (4.31%), corresponding to higher odds of a false alarm in the UT condition ($OR = 1.79$). See Fig. 4 for results.

We further analysed the results of the subjective mental effort scale and CSQ-VR. Due to the data not being normally distributed, we applied the Friedman test. We found no significant differences for mental effort or for any of the categories in the CSQ-VR scale. However, the UT condition showed larger variability ($Md = 7.0[5.5, 8.0]$) compared to OT ($Md = 7.0[6.0, 7.0]$), ON ($Md = 7.0[6.0, 7.0]$), and baseline ($Md = 6.0[6.0, 7.0]$). See Fig. 5 for results on subjective mental effort.

Twelve people expressed feedback regarding the resets. The resets were largely considered disruptive or distracting, especially in relation to the cognitive task ("*The resets were very distracting. Every single time it happened I lost track of the task.*", P16). Some participants stated an increase in dizziness ("*Felt dizzy when I had to do a full turn but was okay during walking*", P5) and discomfort during the resets ("*Uncomfortable, it was not pleasant. Labyrinth was not a problem, it was the turning that was uncomfortable.*", P7).

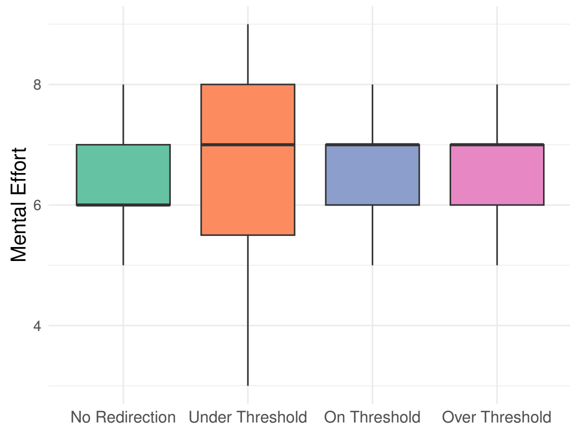

Figure 5: The UT condition showed higher variability in subjective mental effort.

5 Discussion

We found that performing a dual task below the DT affected performance. Accuracy in the 2-back task in the UT condition was significantly lower compared to the baseline condition. Similarly, participants were more likely to press the button to indicate a match when there was none (a false alarm) in the UT condition compared to baseline. This was a surprising finding, as we expected performance to drop as the noticeability of the redirection increased, in line with previous findings in the literature [2, 14]. Within our sample, UT had an approximate detection rate of 62.5%. At higher levels of noticeability, participants may be able to cognitively compensate for this change, potentially contributing to less variability in performance. Furthermore, as we used a pooled DT for this pilot, it is possible that individual sensitivities shaped the results. Compared with prior studies that consist of the participant walking a path in an open environment, our dual task was performed during labyrinth navigation with resets, which may have affected how redirection interacted with cognitive performance.

Interestingly, despite almost all participants expressing that the resets were distracting, the varying reset rates were not shown to affect dual-task performance. Nonetheless, considering the consistent negative feedback regarding the resets, they are likely best avoided to provide a stable user experience. For our next study, we aim to repeat the experiment in a hall large enough to perform the task without any resets. Furthermore, in this study we tested for the DT at a participant-pool level. In our next study, we will increase the sample size and expand the testing for the DT task to calculate the psychometric curve of every participant, thereby computing more accurate results on an individual level.

6 Conclusion

This paper describes the results of a pilot study on how redirected walking applied below, at, or above the DT impacts cognitive load. We found that applying smaller gains under the DT affected performance in the dual task. While the reset rate did not affect performance, user feedback indicated it to be an unpleasant and distracting experience. In future work, we will expand the experiment to estimate individual DTs and recruit a larger, more gender-balanced sample with fully counterbalanced conditions to assess the robustness of our findings.

Acknowledgments

This work was funded by the Hasler Foundation (Project ID 23049).

References

[1] Olivier Beauchet, Véronique Dubost, Kamiar Aminian, Regis Gonthier, and Reto W Kressig. 2005. Dual-task-related gait changes in the elderly: does the type of cognitive task matter? *Journal of motor behavior* 37, 4 (2005), 259–264.

[2] Gerd Bruder, Paul Lubas, and Frank Steinicke. 2015. Cognitive Resource Demands of Redirected Walking. *IEEE transactions on visualization and computer graphics* 21, 4 (April 2015), 539—544. doi:10.1109/tvcg.2015.2391864

[3] David Engel, Cristóbal Curio, Lili Tcheang, Betty Mohler, and Heinrich H. Bülthoff. 2008. A psychophysically calibrated controller for navigating through large environments in a limited free-walking space. In *Proceedings of the 2008 ACM Symposium on Virtual Reality Software and Technology* (Bordeaux, France) *(VRST '08)*. Association for Computing Machinery, New York, NY, USA, 157–164. doi:10.1145/1450579.1450612

[4] Peizhong Gao, Keigo Matsumoto, Takuji Narumi, and Michitaka Hirose. 2020. Visual-Auditory Redirection: Multimodal Integration of Incongruent Visual and Auditory Cues for Redirected Walking. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. Institute of Electrical and Electronics Engineers Inc., NY, USA, 639–648. doi:10.1109/ISMAR50242.2020.00092

[5] Miguel A. Garcia-Perez. 1998. Forced-choice staircases with fixed step sizes: asymptotic and small-sample properties. *Vision Research* 38, 12 (1998), 1861–1881. doi:10.1016/S0042-6989(97)00340-4

[6] Maarten Gerritse, Michael Rietzler, Christof Van Nimwegen, and Julian Frommel. 2024. The Effect of Spatial Audio on Curvature Gains in VR Redirected Walking. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 685, 10 pages. doi:10.1145/3613904.3641919

[7] Timofey Grechkin, Jerald Thomas, Mahdi Azmandian, Mark Bolas, and Evan Suma. 2016. Revisiting detection thresholds for redirected walking: combining translation and curvature gains. In *Proceedings of the ACM Symposium on Applied Perception* (Anaheim, California) *(SAP '16)*. Association for Computing Machinery, New York, NY, USA, 113–120. doi:10.1145/2931002.2931018

[8] David M. Green. 1990. Stimulus selection in adaptive psychophysical procedures. *The Journal of the Acoustical Society of America* 87, 6 (06 1990), 2662–2674. arXiv:https://pubs.aip.org/asa/jasa/article-pdf/87/6/2662/11826721/2662_1_online.pdf doi:10.1121/1.399058

[9] C. Hutton, S. Ziccardi, J. Medina, and E. Suma Rosenberg. 2018. Individualized Calibration of Rotation Gain Thresholds for Redirected Walking. In *ICAT-EGVE 2018 - 28th International Conference on Artificial Reality and Telexistence and 23rd Eurographics Symposium on Virtual Environments*. The Eurographics Association, Netherlands, 61–64. doi:10.2312/egve.20181315

[10] Jason Jerald, Tabitha C Peck, Frank Steinicke, and Mary C Whitton. 2008. Sensitivity to scene motion for phases of head yaws. *Review Literature And Arts Of The Americas* 126 (2008), 155–162. Issue 7. doi:10.1145/1394281.1394310

[11] Panagiotis Kourtesis, Josie Linnell, Rayaan Amir, Ferran Argelaguet, and Sarah E. MacPherson. 2023. Cybersickness in Virtual Reality Questionnaire (CSQ-VR): A Validation and Comparison against SSQ and VRSQ. *Virtual Worlds* 2, 1 (2023), 16–35. doi:10.3390/virtualworlds2010002

[12] Eike Langbehn, Paul Lubos, and Frank Steinicke. 2018. Evaluation of Locomotion Techniques for Room-Scale VR: Joystick, Teleportation, and Redirected Walking. In *Proceedings of the Virtual Reality International Conference - Laval Virtual* (Laval, France) *(VRIC '18)*. Association for Computing Machinery, New York, NY, USA, Article 4, 9 pages. doi:10.1145/3234253.3234291

[13] Jieun Lee, Seokhyun Hwang, Aya Ataya, and SeungJun Kim. 2024. Effect of optical flow and user VR familiarity on curvature gain thresholds for redirected walking. *Virtual Reality* 28, 1 (29 Jan 2024), 35. doi:10.1007/s10055-023-00935-4

[14] Fariba Mostajeran, Sebastian Schneider, Gerd Bruder, Simone Kühn, and Frank Steinicke. 2024. Analyzing Cognitive Demands and Detection Thresholds for Redirected Walking in Immersive Forest and Urban Environments. In *2024 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*. IEEE Computer Society, New York, NY, USA, 61–71. doi:10.1109/VR58804.2024.00030

[15] Christian T. Neth, Jan L. Souman, David Engel, Uwe Kloos, Heinrich H. Bulthoff, and Betty J. Mohler. 2012. Velocity-Dependent Dynamic Curvature Gain for Redirected Walking. *IEEE Transactions on Visualization and Computer Graphics* 18, 7 (2012), 1041–1052. doi:10.1109/TVCG.2011.275

[16] Anh Nguyen, Yannick Rothacher, Evdokia Efthymiou, Bigna Lenggenhager, Peter Brugger, Lukas Imbach, and Andreas Kunz. 2020. Effect of Cognitive Load on Curvature Redirected Walking Thresholds. In *26th ACM Symposium on Virtual*

Reality Software and Technology (Virtual Event, Canada) *(VRST '20)*. Association for Computing Machinery, New York, NY, USA, Article 17, 5 pages. doi:10.1145/3385956.3418950

[17] Anh Nguyen, Yannick Rothacher, Bigna Lenggenhager, Peter Brugger, and Andreas Kunz. 2018. Individual Differences and Impact of Gender on Curvature Redirection Thresholds. In *Proceedings of the 15th ACM Symposium on Applied Perception* (Vancouver, British Columbia, Canada) *(SAP '18)*. Association for Computing Machinery, New York, NY, USA, Article 5, 4 pages. doi:10.1145/3225153.3225155

[18] Niels Christian Nilsson, Tabitha Peck, Gerd Bruder, Eri Hodgson, Stefania Serafin, Mary Whitton, Frank Steinicke, and Evan Suma Rosenberg. 2018. 15 years of research on redirected walking in immersive virtual environments. *IEEE computer graphics and applications* 38, 2 (2018), 44–56.

[19] Fred GWC Paas. 1992. Training strategies for attaining transfer of problem-solving skill in statistics: a cognitive-load approach. *Journal of educational psychology* 84, 4 (1992), 429.

[20] Tabitha C. Peck, Henry Fuchs, and Mary C. Whitton. 2011. An evaluation of navigational ability comparing Redirected Free Exploration with Distractors to Walking-in-Place and joystick locomotio interfaces. In *2011 IEEE Virtual Reality Conference*. IEEE Computer Society, New York, NY, USA, 55–62. doi:10.1109/VR.2011.5759437

[21] Sharif Razzaque, Zachariah Kohn, and Mary C. Whitton. 2001. Redirected Walking. In *Eurographics 2001 - Short Presentations*. Eurographics Association, Netherlands, 6 pages. doi:10.2312/egs.20011036

[22] Frank Steinicke, Gerd Bruder, Jason Jerald, Harald Frenz, and Markus Lappe. 2010. Estimation of detection thresholds for redirected walking techniques. *IEEE Transactions on Visualization and Computer Graphics* 16 (1 2010), 17–27. Issue 1. doi:10.1109/TVCG.2009.62

[23] Andrew B Watson and Denis G Pelli. 1983. QUEST: A Bayesian adaptive psychometric method. *Perception & psychophysics* 33, 2 (1983), 113–120.

[24] Niall Williams and Tabitha C. Peck. 2019. Estimation of Rotation Gain Thresholds for Redirected Walking Considering FOV and Gender. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, NY, USA, 1229–1230. doi:10.1109/VR.2019.8798117

[25] Marjorie Woollacott and Anne Shumway-Cook. 2002. Attention and the control of posture and gait: a review of an emerging area of research. *Gait & posture* 16, 1 (2002), 1–14.

[26] Ruimin Zhang and Scott A. Kuhl. 2013. Human sensitivity to dynamic rotation gains in head-mounted displays. In *Proceedings of the ACM Symposium on Applied Perception* (Dublin, Ireland) *(SAP '13)*. Association for Computing Machinery, New York, NY, USA, 71–74. doi:10.1145/2492494.2492514