Impact of Starting Position on Decision-Making in Virtual Reality

Valentina Gorobets[a], Mathieu Lutfallah[b], Khashayar Ilbegi Teymouri and Andreas Kunz[c]
Institute for Machine Tools and Manufacturing, Swiss Federal Institute of Technology Zurich, Clausiusstrasse 33, Zurich, Switzerland
{gorobets, lutfallah, kunz}@iwf.mavt.ethz.ch

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Abstract: Few studies have explored how a user's initial starting position or physical obstacles in reality affect decision-making in virtual reality (VR), particularly when natural walking is used for locomotion. In this paper, we examine how the starting position in the real world influences walking path decisions in VR. 24 participants were positioned next to a physical wall before putting on a VR headset and then asked to walk through a narrow virtual corridor, making a left or right turn at a decision point. To ensure safety, we employed redirected walking techniques to subtly steer participants away from the real wall. Our results indicate that users remain aware of their physical starting position, influencing their directional choices in VR.

1 INTRODUCTION

In recent years, VR has become more accessible to the end-user and industry, being utilized not only for entertainment purposes, but also for training. (Xie et al., 2021) lists some of the possible VR training domains: first responder training, medical training, military training, transportation, workforce training, and interpersonal skills training. To effectively train people in VR and later apply the results of VR training to real-life scenarios, it is crucial to study the decision-making process in VR and identify potential factors that may influence it. One such factor can be a user's awareness of the physical boundaries of the real environment they are in.

To explore virtual environments (VEs), various locomotion techniques can be used, such as natural walking, walking-in-place, treadmills, or teleportation (as shown in (Usoh et al., 1999)). Natural walking is the most intuitive of these; however, it also requires enough physical space to allow users to freely walk and navigate in the VE. Currently, VR research does not concentrate on the effect of the starting position of the user in the real world on human behavior in VR. However, previous research by (Interrante et al., 2007) has demonstrated that the real-world space where the virtual experience begins, impacts the user's experience in VR. Their findings indicate that spatial perception accuracy in immersive virtual environments can be influenced by starting in a real-world space that is later replicated virtually. However, to our knowledge, no work has explored the effects of the paths users take in VR based on their initial physical position. While the effect of the starting position in reality might be negligible when the implemented locomotion technique does not require natural walking, we want to focus our research on natural walking and investigate how a starting position may affect the walking paths.

[a] https://orcid.org/0000-0002-8615-5972
[b] https://orcid.org/0000-0001-7863-8889
[c] https://orcid.org/0000-0002-6495-4327

1.1 Spontaneous Alternation Behaviour

To better understand path decisions, it is important to introduce the concept of Spontaneous Alternation Behaviour (SAB). SAB describes an animal's tendency to avoid repeating choices when exploring a maze. (Nguyen et al., 2017) investigated the potential presence of this behaviour in humans using VR. To determine its existence, a study was conducted in which a virtual maze of equal corridors, consisting of an initial 90° forced turn, followed by three T-junctions, was designed. A forced turn describes a turn in any direction that is imposed on the user, meaning no other path is available. The overall alternation rate in VR was found to be 72%. Their studies showed that also in humans, the decision-making in path selection is influenced by previous walking experiences, such as forced turns, given that no other visual effects influence the the decision-making process.

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1.2 Path Decisions Influenced by Visual Differences

(Abu-Safieh, 2011) examined the effect of visual differences, such as brightness and color, on decision-making in a maze. Two different mazes were designed for this purpose. One focused on brightness differences between corridors, and the other on color differences. The results indicated that there was a high preference for brighter corridors, i.e., corridors with windows, and cold-colored corridors (e.g., blue, green, or white). (Vilar et al., 2013) explore the impacts that width and brightness have on path decisions. Four different experiments were designed. All comprised T-junctions and F-junctions with various manipulations applied to them. Similar to (Abu-Safieh, 2011), they utilized brightness modifications as well. However, contrary to (Abu-Safieh, 2011), instead of experimenting with colors, they researched the influence of the width of a corridor. The results yielded a preference for wider corridors, with ca. 70% of the choices being the wider corridor. Also, the results showed a preference for brighter corridors, with approximately 84% of the outputs for that experiment preferring the brighter corridor. However, when it came to choosing between brighter or wider, brightness ended up having a stronger influence on the users' choices. The narrower but brighter corridor was preferred over the wide but darker one. Additionally, when combining the properties, even higher percentages of 87% were reached.

1.3 Redirected Walking

In our experiment, the user's starting position is next to the side wall. To seamlessly steer them away from it, we use the Redirected Walking (RDW) technique, as initially introduced by (Razzaque, 2005). Redirected walking with gains involves subtly manipulating a user's movements in VR by applying rotation, translation, or curvature gains. When being applied below a perception threshold (Lutfallah et al., 2024), (Steinicke et al., 2010), these gains alter a user's visually perceived direction, speed, and curvature with regard to the real walking trajectory, enabling them to navigate a larger VE within a limited physical space. This creates a seamless and immersive experience by preventing collisions with real-world boundaries.

While some research exists on the influence of VEs on a human's decision-making process for path selection, no research exists on the influence of the real environment, which the user sees before putting on the headset, on their decisions regarding path selection in the VE. Thus, our research findings will sensitize future research on redirection by addressing unwanted biases stemming from the real environment. This paper first describes the methodology of our experiments, followed by a description of the user study. We then discuss the results and give an outlook on future work.

2 METHODOLOGY

The goal of this work was to investigate the influence of the perceived starting position in the physical space on user decisions when making decisions in a virtual maze. To achieve this, we developed a VE with a T-shaped corridor where the user traverses it using natural walking and must make a turn at the junction. We developed the environment using Unity version 2022.3.16f1 with the OpenXR library. The VE was streamed from a PC to the Pico 4 Enterprise via WiFi. The available tracking space was $7m \times 10m$, in which users always starting next to a physical wall (see Figure 1.

The layout of the implemented corridor can be seen in Figure 2. We used a monochromatic texture to eliminate any potential influences stemming from the VE. The side passageways were identical and dimly lit, so the user could not see the end. For the experiments, one side of the corridor led to a physical wall (critical turn (CT) in Figure 2) since the user starts next to the environment boundaries. To allow the user to walk a certain distance if that CT corridor is chosen, we used curvature gains, which represent the injection of rotation while the user perceives to walk straight, subtly directing them away from the physical wall. The employed curvature gain was restricted to a radius of 16 meters, which is more conservative than the thresholds described (Steinicke et al., 2010). Using such a wide radius also avoids triggering the SAP behavior in humans, as described by (Rothacher et al., 2020).

Since the awareness of the physical boundaries and thus their effect on decision making in VR might decay over time and walked distance in VR, the effects of different corridor lengths were studied in this work. The lengths used were 7, 5, and 3 meters, and the same experiment was conducted on both the left and right sides of the room. Figure 3 shows the user path along the corridor when curvature gains are applied. This resulted in total in 6 conditions for the user study, and in 5 games between them.

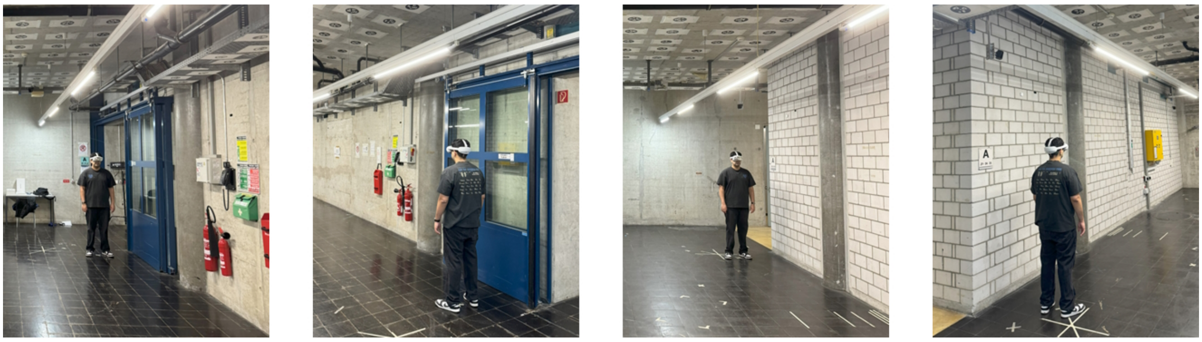

Figure 1: The tracking space where the user study has been conducted. Depending on the user's starting position, the physical wall is either on the left or the right side, hence resulting in left or right critical turn (CT).

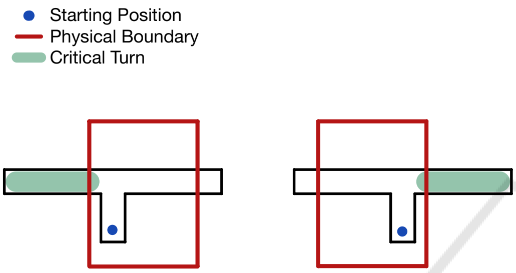

Figure 2: Placement of the VE corridor with respect to the physical space boundaries.

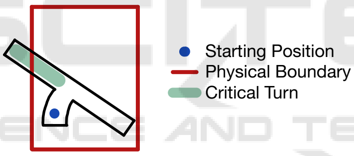

Figure 3: Actual user path in the physical space due to the employment of curvature gains.

3 USER STUDY

To gather data about user decisions in the implemented VE, a user study was conducted. Participants were recruited through a poster shared at the university. The only criterion for participation was the ability to walk. The procedure of the study is shown in Figure 4.

After welcoming the participants, they had to fill out a consent form. Then, they received an explanation of the overall study sequence, consisting of the introduction, the two parts of the questionnaire, and the VR sessions. They then filled out the first part of the questionnaire which consisted of demographic questions and the simulator sickness questionnaire (SSQ) as presetned by (Kennedy et al., 1993). Following this, the user received a short tutorial about the Pico 4 Enterprise and its controllers, and the guidelines were described, as well as the VEs and necessary

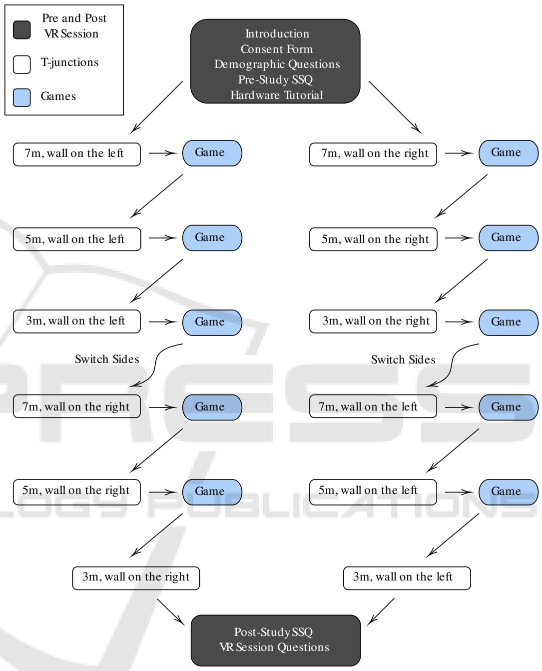

Figure 4: User study procedure and the two conditions of the nearby physical wall being on the left or right side of the starting position. The game of each round depends on the assigned order.

steps. Next, participants were instructed to wear the headset, adjust it, and adjust the correct interpupillary distance if necessary. Then, they were guided to the starting position without wearing the HMD so they could see the nearby wall. The experiment started with the 7-meter corridors, followed by the 5-meter and then 3-meter corridors. This sequence was repeated for the other side of the physical room (see Figure 2). The starting side was divided equally among the users, with half starting on the right and half on the left. The starting positions were placed at a 0.7m distance from the corresponding wall and marked on the floor to simplify the positioning of the users before the start of each experiment round. The descending order of lengths was chosen because starting with 7 meters allowed the user to be redirected the most, enabling them to walk the furthest in the critical direction before reaching the boundaries again. This created the impression that they would be able to walk similarly in future conditions, while in the 3-meter condition, only two steps are possible in the CT direction.

Once the user had walked through the corridor, made a decision on which side to go, and walked a few steps in that direction, the experiment was finished, and a stop sign appeared. Then, the user is taken to a new scene where they can play a game. The games served two purposes: first, to prevent users from remove the HMD immediately after finishing the experiment to prevent them from realizing the use of curvature gains; second, the games required walking to help the user forget the decision they made in the previous condition. After finishing the game, the user had to take off the HMD and walk again to the starting position next to one of the walls, allowing the second experiment to start. This led the user to see the starting position again in the physical space.

The games used were rather simple and only ensured that the user needed to walk. There were in total 5 games for the 6 conditions. In the first game, the user had to pick apples from trees and place them in a box in the center of the room. The second and third game involved shooting balloons, where the user had to walk to the reloading station after shooting 10 bullets. In one game, the balloons were spread everywhere, while in the other, there were separating walls that the user had to navigate to see the targets. The fourth game involved solving mathematical equations using cubes placed around the space. The user had to grab the cubes and place them on a board to complete an equation. Finally, the last game consisted of grabbing colored cubes and placing them in the correct basket of the same color.

The order of the games between the conditions was also permuted so that none of the users had exactly the same sequence, ensuring that in the set of combinations, no pair of games appeared in the same position twice. After finishing the complete study in VR, each user had to answer again the SSQ questionnaire, and some experiment-specific questions. These consisted of describing the effects of the walls on their decision and the strategy followed to make the decision at the junction. Additional questions were added to detect the perception of curvature gain. To obscure the focus on curvature gain, some questions referred to non-existent aspects, with the key question about curvature gain hidden among them. This procedure is inspired by the work of (Suma et al., 2011). For example, one of the obscuring questions asked the user if they felt they were walking faster or slower between the environments.

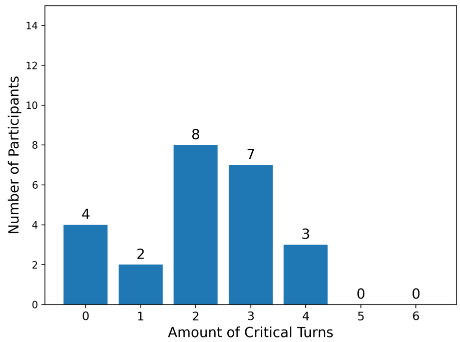

Figure 5: Amount of participants per number of critical turns.

4 RESULTS AND DISCUSSION

A total of 24 individuals were recruited, 21 male and 3 female. All participants had normal or corrected-to-normal eyesight. They consisted mostly of bachelor's and master's students. Their ages ranged from 20 to 28 years. Different levels of experience with VR equipment are represented in the recruited pool, ranging from complete novices to those with more than 100 hours of experience. We recorded 6 paths per participant, resulting in a total of 144 paths.

The SSQ scores were computed for both the pre- and post-questionnaire phases. The average difference between the total scores was 2.65 ± 16.28, with 14 participants having lower or unchanged scores after the testing phase. This indicates that the experiments did not induce significant cybersickness in participants. It should be noted that there was one outlier with a difference of 44.9. However, during this experiment, some connection problems occurred, which likely led to this result. Since the participant did not report any discomfort in the informal feedback, we decided to retain their data.

4.1 General Findings

Out of the 144 paths obtained, 93 were Non-Critical Turns (NCTs) (see Table 1). That corresponds to approximately 64.58%, i.e., nearly two-thirds of the paths. On average 3.875 out of 6 of the participants' paths avoided CT. So, each person chose on average 2 CTs. In Figure 5, is shown the number of participants who chose a certain amount of CTs. No user chose 5 or more CTs. In addition, the majority chose 4 or more paths involving NCTs.

Table 1: Overall Recorded Path Decisions.

	Non-critical Turns	Critical Turns	Total
Amount	93	51	144
Percentage	64.58%	35.42%	100%

4.2 Correlation Between CTs and Wall Location

When looking at the number of paths leading away and towards the close wall grouped by the wall location (see Figure 6), we see that when the wall is on the left, exactly $1/3$ of the paths are CT. When the wall is on the right, a similar behavior is observed, though slightly more paths (37.5%) involving the CT. Our null hypothesis is formulated in the following way:
H_0: The side on which a participant starts the experiment (wall to the left or to the right of the user) does not have a significant impact on the decision-making.
Using Fisher's exact test, we get that $p > 0.05$. Therefore, H_0 cannot be rejected, which proves that the initial position of the wall (to the left or to the right of the user) did not significantly affect the number of the taken critical turns.

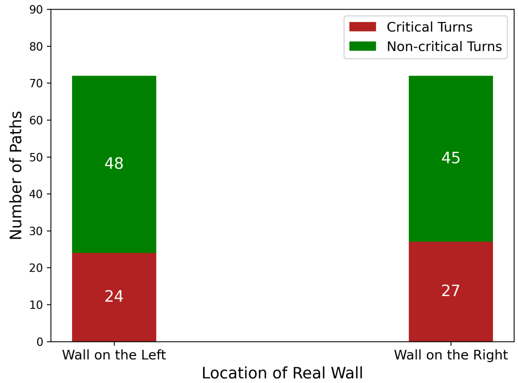

Figure 6: Path decisions by wall location.

4.3 Correlation Between CTs and Corridor Length

Grouping the results by corridor length, an interesting behavior is shown. The results for the corridors with lengths $3m$ and $7m$ show the tendency of the participants to avoid critical turns. However, for $5m$, we have exactly 50% of CTs. Our null hypothesis is formulated in the following way:
H_0: The longer the distance up to the decision point, the more paths will involve a CT, as the participants tend to forget the physical boundary after walking a longer distance.
A pairwise Fisher's test was conducted to test our hypothesis, with a Bonferroni correction applied due to multiple comparisons. Firstly, Fisher's exact test for the conditions with corridor lengths $3m$ and $7m$ yields that $p > 0.01$, and thus is not statistically significant. For conditions with lengths $5m$ and $7m$, we get $p > 0.01$, and the same goes for lengths $5m$ and $3m$. In conclusion, H_0 cannot be rejected for any of these. Hence, it cannot be proven that the lengths had an impact on the decision-making. This confirms the finding by Ngyuen et al. (Nguyen et al., 2017), who also stated that alternation behavior neither decays nor increases over time.

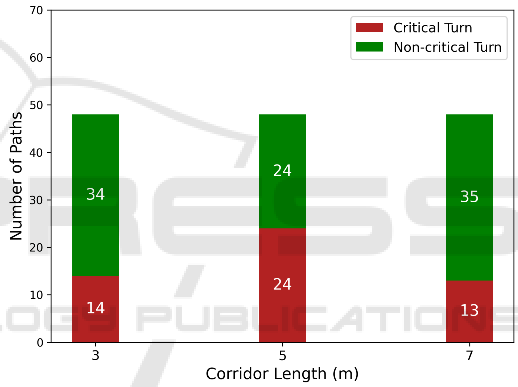

Figure 7: Path decisions by corridor length.

4.4 Correlation Between CTs and Physical Boundaries Effect

From the 24 participants, 7 stated that the walls did not affect their turn decision. Comparing the percentages of path directions in relation to the effect of the physical walls (see Table 2), we observe that the percentage of paths heading towards the wall is higher for people who stated that they were not affected by the walls than those who were. Still, the majority of paths diverted from the nearby wall.

4.5 Correlation Between CTs and the Round Number

The results yielded a clear preference to avoid the wall when it comes to the first, third, fourth, fifth, and sixth rounds, where the majority of participants chose the path avoiding the CT. For the first and last rounds,

Table 2: Path decisions based on awareness of boundaries.

Decision affected by the Physical Walls	Non-critical Turns	Non-critical Turns [%]	Critical Turns	Critical Turns [%]
No	24	57.14%	18	42.86%
Yes	69	67.65%	33	32.35%

Table 3: Alternation rates of critical and non-critical turns.

Rounds	1st - 2nd	2nd - 3rd	4th -5th	5th - 6th
$P(CT\|NCT)$	0.6842	0.3	0.4375	0.3571

Table 4: Alternation Rates of the Turn Direction.

Rounds	1st - 2nd	2nd - 3rd	4th -5th	5th - 6th
$P(X\|Y)$	0.7083	0.5	0.5	0.5833

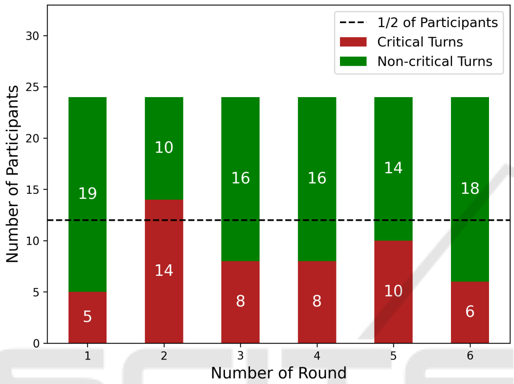

Figure 8: Path decisions by round number.

nearly 80% chose to move away from the physical boundary. Whereas, for the second round the behavior is vastly different, with the majority choosing to walk towards the obstacle. Still, in five out of the six rounds, the majority of paths avoid the CT (see Figure 8). Table 3 shows the different alternation rates ($P(CT|NCT)$) of choosing a CT given that the previous choice was not a CT (NCT) when comparing two consecutive rounds of the T-junction experiment. The probability for the second round is significantly higher, while for the remaining rounds, the probability stays below 0.5.

4.6 Correlation Between the Current and Previous Turn Choices

Table 4 shows the different alternation rates when comparing the two consecutive rounds of the T-junction experiment. $P(X|Y)$ is the probability of choosing direction X given that the previous choice was direction Y. We implemented the mini-games between different rounds to prevent the SAB in two consecutive rounds. However, as it is seen from the Table 4, $P(X|Y)$ between rounds 1 and 2 is rather high. Our assumption is that this is linked to the curiosity of the participants to explore another turn of the VE and see what will happen. As the majority of the participants tried to avoid the CT in the first round due to their awareness of the physical wall nearby, some of them reported their interest in taking it in the next round.

5 CONCLUSION

In this paper, we presented an approach to investigate the effect of the starting position on the walking path and decision-making in VR. We hypothesized that starting next to the physical wall triggers participants to take the non-critical turn and steer away from the real wall to avoid collision. To implement such an environment, we used a redirected walking technique that steered participants away from the wall to prevent them from colliding with it if a critical turn was taken. To mitigate participants' spatial awareness, we integrated mini-games in between different rounds. Our results showed that in the initial round, participants tended to avoid critical turns due to an awareness of their starting position near the wall. However, in the second round, more than half of the participants chose to take a critical turn, mentioning during interviews that they were aware of the environment but wanted to explore the consequences of taking a critical turn.

Our research highlights the need to consider the spatial awareness of the users when natural walking is required. Further research can be broadened to not only consider the starting position next to the wall but also investigating the influence of other obstacles that are present in the physical environment.

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