Revisited Threshold Detection in Redirection Techniques

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ABSTRACT

Overlapping rooms and translation gains are two redirection techniques that enable users to navigate larger virtual environments within a limited physical space. It is crucial to apply these methods subtly to ensure user immersion, as previous research has identified specific detection thresholds. These thresholds have been determined in experiments where users were aware of the applied method and engaged in non-immersive tasks. In this study, we investigate whether naive users participating in a shooting game are less likely to detect these redirection thresholds. We conducted a user study involving shooting randomly appearing balloons. Our findings suggest that detection thresholds may be higher than those previously reported in the literature, highlighting the need for further investigation to comprehensively quantify these threshold values. This research contributes to an emerging trend in this field, emphasizing the importance of refining threshold assessments for more effective redirection techniques in virtual environments.

CCS CONCEPTS

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

KEYWORDS

Locomotion, Walking, Virtual Reality, Redirection, Redirected Walking

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1 INTRODUCTION

Virtual Reality (VR) is a rapidly emerging technology with applications in both research and entertainment. In fact, the gaming sector alone is projected to generate $2.4 billion in revenue by the end of 2024[1]. VR games such as Beat Saber and Superhot VR became incredibly popular, captivating audiences worldwide. The rising popularity of VR applications require improving numerous interactions that are necessary to create compelling VR experiences. One such interaction is locomotion.

Navigation in the real world occurs by means of walking or running, but achieving a realistic simulation of such locomotion techniques in virtual environments (VE) is an ongoing challenge. Powered shoes [10] and omnidirectional treadmills [9] have been investigated as interfaces for locomotion. However, natural walking has been proven to be the ideal locomotion technique based on criteria like presence, cyber-sickness, and usability [25]. Although natural walking allows an immersive user experience, implementing it can be challenging due to a limited physical tracking space.

On average, VR users have a tracking space of approximately 25 square meters. That amount is minimal, considering that numerous virtual environments (VEs) offer larger spatial dimensions. Thus, redirection techniques have been presented to help users overcome this challenge. Various researchers have tried to classify these methods. Suma et al. [22] distinguished them between discrete and continuous, overt and subtle, reorientation and repositioning. Others have tried to categorize them between manipulation of self-motion and manipulation of the virtual scene [23]. Subtle redirection methods are preferred since they allow for a higher immersion and a smaller break of presence. Combining such subtle methods with game elements have been explored [12, 13]. Other researchers have focused on determining levels where the user would start noticing such manipulations and defined thresholds [5, 21, 23]. In this work, the thresholds values of two techniques are studied, given the task of shooting balloons: redirected walking (RDW) and overlapping architecture (OA).

RDW is a technique where the mapping between physical and virtual movement is modified. This can be done via three possibilities: rotational gains that alter the angular relationship between a user's physical rotation and their perceived rotation in virtual reality, translation gains that change the mapping of the distance walked by the user, and curvature gains that cause the user to deviate from walking in a straight path to a curved one. On the other hand, OA refers to the redirection method where multiple virtual rooms coincide and occupy the same physical space. Even though these techniques are applied, users may still approach the boundaries and encounter physical obstacles. In such cases, resets [28] are implemented, requiring the user to stop and perform a specific action that reorients them towards the available space in the physical environment.

In most of the work focusing on estimating the detection thresholds, users were aware of the purpose of the study [21, 23]. This limits the applicability of such results in applications where users won't be aware of the study's purpose. Secondly, some researchers

[1]https://www.zippia.com/advice/virtual-reality-statistics/, accessed on 9.4.23

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have investigated the effect of distractors in such "dual task" environments but used rather simple distractors that aren't applicable to more general use cases [29]. Peck et al. [15] have shown that having distractors matching the environment context makes the user less prone to noticing the redirection used. However, the work mainly focused on having distractors shown when resets are triggered.

This was followed by numerous studies investigating the use of redirection with distractors in gaming contexts. These studies demonstrated that distractors can be effectively combined with rotational gains. Sra et al. [19] describe the integration of distractors with visibility control techniques, such as reduced field of view, limited viewing distance, tilted viewing angles, and shallow depth of field. An example includes combining a limited depth of view, as experienced when looking through a telescope, with rotational gains and directing the user's attention to a specific moving distractor. However, a significant limitation is that these distractors and techniques are typically employed for a short duration when the user is reoriented close to the boundaries of the physical environment. Discrete periods when distractors are presented have also been examined, as in [4], where a ball is used as a distractor, and in [1], where a dragon is introduced during a reset. In these studies, the threshold detection primarily focuses on rotational gains, and no distractors are presented while the user navigates away from boundaries. The objective of this work is to concentrate on translation gains and OA, which are less explored, while implementing a continuous interactive task. The primary contributions of this work are as follows:

- Estimation of detection threshold of translation gains with a mainstream distractor "shooting".
- Estimation of detection threshold of overlapping rooms with a mainstream distractor, "shooting".
- Presentation of a modified 2AFC questionnaire to detect the naive user's perception of the redirection technique.

2 RELATED WORK

In the subsequent section, we provide a comprehensive overview of prior research pertaining to the estimation of detection thresholds. This review encompasses a range of studies that have significantly contributed to our understanding of how users perceive and react to various manipulations in virtual environments, particularly in the context of redirected walking and impossible spaces.

2.1 Estimating thresholds for RDW gains

The concept of RDW was first introduced by Razzaque et al. [17]. Later, he showed that the redirection can be used without making the user aware of it and without causing simulator sickness [16]. Razzaque's work laid the foundation for subsequent work in this field, especially regarding detection thresholds. For instance, according to Steinicke et al. [21], distances can be scaled down by 14% or scaled up by 26% before users become aware of the manipulation. To mitigate users' sensitivity to these manipulations, researchers have explored the use of distractors which divert users' attention, preventing them from detecting the applied redirection. Williams et al. [29] discovered that distractors like a moving deer along the horizon had a significant impact on the detection of rotation gains. It is worth noting that this particular study only examined rotation gains. These findings underscore the need to explore interactive distractors that are more generally applicable. In a study by Schmelter et al. [18], researchers investigated the influence of interactions commonly found in video games on rotation gain thresholds. The experiments showed that interactions such as "Focus", "Pick Up", "Throw", "Shoot", and "Fight" could be used as distractors for redirected walking. By incorporating a shooting task as a distractor, which is prevalent in video games, the researchers concluded that there is a definite improvement of the rotation gain threshold compared to the no-interaction scenario. Yet again, this work considered only rotation gain thresholds, suggesting the need to explore the influence of continuous task-based distractors on other redirected walking gain thresholds, e.g., translation gains.

2.2 Estimating thresholds for overlapping rooms

Redirection can also be applied to the VE itself [23]. OA is a technique that optimizes tracking space utilization by overlapping neighboring rooms. The goal is to create the illusion that these rooms occupy separate areas while, in reality, they share the same physical space. The overlap occurs when the user traverses a corridor and the wall separating the two rooms shifts. Determining the maximum allowable overlap before users perceive it as impossible is an ongoing research topic. Vasylevska et al. [24] presented an algorithm that allows continuous generation of corridors and overlapping rooms. In follow-up works [26, 27] they studied the effect of the corridor shape and length on the user's spatial awareness in overlapping rooms. Langbehn et al. [20] demonstrated the possibility of combining overlapping rooms with bending gains to further distort the virtual environment, allowing for more compression. Lutfallah et al. [14] investigated the usage of RDW algorithms in combination with overlapping rooms.

In a paper by Ciumedean et al. [3], researchers investigated the impact of an interactive distractor - a task involving evasion from a CCTV camera — on the detection threshold. They demonstrated a possibility of achieving a higher overlap, reaching up to 68%. In subsequent research [2], they explored the feasibility of using overlapping rooms in "open rooms" and "open corridors". In the latter, users could see the adjacent room, whereas "open corridors" lacked outer walls. They discovered that the open corridor scenario yielded the highest overlap before being detected by users. The authors hypothesized that this might be due to the surrounding nature visible to the user, which served as a distractor.

3 IMPLEMENTATION

For this study, the chosen distractors will involve shooting balloons. We will explore detection thresholds for translation gains and OA. To develop the virtual environments, Unity software and the VIVE Focus 3 headset were utilized. The VE was streamed via Wi-Fi to the head mounted display from a PC with an Intel core i9-10900K processor and an NVIDIA Ge-Force RTX 3090. Two distinct environments were created, each tailored to the specific requirements of the individual experiment.

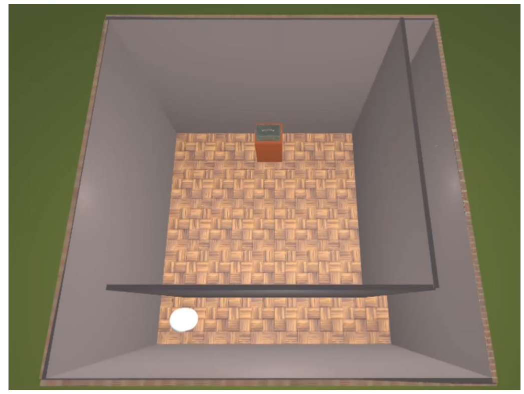
3.1 Experiment 1: Overlapping Architecture

In the OA experiment, we needed two neighbouring rooms. Thus, we designed a building of size $4m \times 4m$ containing two adjacent rooms that share a common wall. These rooms were connected with a corridor. The layout of the building was inspired by the VE used in the work by Suma et al. [23]. Inside each room, there was a table with an ammunition box. In total, there were nine transparent colliders (three in each room and the corridor) that would spawn a balloon once they are hit. Since we wanted the participants to look around while walking, we needed the balloons to appear at a random place in the room and to move vertically. This was to prevent the prediction of the balloon's location and to force vertical head movements. Once the transparent collider was hit, a balloon would spawn randomly in the room where the collider is located. The balloons would appear close to the ground and slowly rise towards the ceiling. To introduce a sense of time pressure, the color of the balloons gradually changed from black to red and then white before eventually exploding. The lifetime of the balloon was set to 7 seconds, allowing it to fully rise up and linger for a few seconds before exploding.

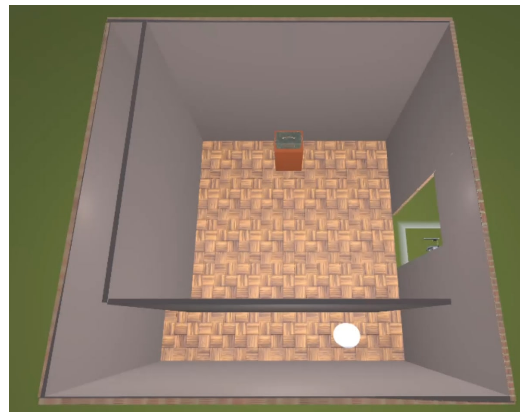
Since shooting was the distractor in this task, we created a gun that the user could grasp. In front of the user, there was a transparent canvas with a text displaying the number of balloons shot and those that already appeared. This was designed so that the users would know how well they were doing, incentivizing them to look around. When a balloon is shot, it explodes with an explosion sound. Moreover, there is a bumping sound when the balloon hits the ceiling, providing an additional clue for the users.

The texture used for the floor in this experiment was a parquet floor arranged in a squared way. This choice was made to give an impression of an ordinary house, such that it would feel natural and thus introduce no additional distraction. The repositioning of the wall between the two rooms is the key component of overlapping architecture. In the center of the corridor, there was a transparent collider. When the user hit this collider, the wall separating the two rooms would shift sideways. The amount of shift depended on the specific level of overlap set for the trial. Additionally, the table with the ammunition box would move, creating the illusion of two separate tables in each room. Figure 1 shows the change in the room layout upon hitting a collider.

We aimed to investigate the extent to which the threshold for room overlap could be increased by introducing a shooting distractor, while keeping the participants unaware of the overlapping rooms. We based our selection of overlap levels on the findings of Suma et al. [23], which identified a 56% overlap as the threshold for reasonably small rooms. Accordingly, the overlaps chosen for each trial were 50%, 65%, and 80%. It should be noted that we tested only these specific thresholds instead of a gradual increase from 0% to 80%. This decision was made to keep the experiment concise and to prevent participants from becoming overly attentive due to the repetitive nature of the trials. This methodology was similarly applied in the experiment involving translation gain.



(a) Top view of room with wall shifted to the right.



(b) Top view of room with wall shifted to the left.

Figure 1: Top view of the building before hitting the transparent collider (top) and after (bottom). White capsule represents the participant. The level of overlap here is set to 80%.

3.2 Experiment 2: Translation Gains

The second experiment focuses translation gains, and thus, we designed a VE where the user would only walk straight. The experiment consists of a narrow 10m × 2.5m corridor outdoors, shown in Figure 2. The narrow nature of the corridor was intended to restrict walking in a curved manner. Similarly to the first experiment, the corridor walls were gray without any texture. At the end of the corridor, there was a table with an ammunition box on top of it. Additionally, there were 8 transparent colliders distributed uniformly between the beginning of the corridor and the ammunition box. Like in experiment one, upon hitting a collider, the balloons spawned randomly within the bounds of the corridor. Thus, eight balloons spawned on the way to the ammunition box and eight on the way back, resulting a total of 16 balloons. The gun, balloons, randomly generated balloon coordinates, score display canvas, and ammunition box worked identically to those in the first experiment. Our objective was to determine the extent to which the threshold for translation gains could be increased by employing a shooting distractor while keeping users unaware of the applied redirection. For each trial, we chose gains based on findings from nine papers that investigated translation gain thresholds, summarized by Fan et al. [6]. This comprehensive review indicated that the lower threshold for translation gains varies between 0.73 and 0.94, while the upper threshold ranges from 1.1 to 1.45. Consequently, we opted for translation gains of 0.75, 0.7, and 0.65 to test the deceleration of user movement in the VE, and gains of 1.4, 1.45, and 1.5 for acceleration.

Figure 2: Top view of corridor used as a VE for the second experiment.

4 USER STUDY PROCEDURE

Participants were recruited from the university community with the sole criterion for participation being the ability to walk. Before the start of the experiments, we refrained from presenting the goal of the user studies to prevent participants from actively searching for clues about the redirection technique. All participats were required to sign a consent form. The simulator sickness questionnaire (SSQ) [11] was answered before and after all user studies. Following this, participants were introduced to the hardware in the Steam VR default room, where they could walk. We instructed the participants to grab the gun, enter the building, and collect the ammunition boxes. While walking, balloons would appear randomly, and participants have to shoot as many of them as possible. Participants were informed that objects might appear behind them, necessitating them to look around. The study procedure is illustrated in Figure 3. The order of the experiments was counterbalanced to ensure that half of the participants started with different experiments.

For the OA experiment, participants engaged in multiple trials with increasing levels of overlap: 0.5%, 0.65%, and 0.8%. Each trial concluded with participants answering a modified two-alternative forced-choice (2AFC) question. If the answer was yes, this experiment concluded; otherwise, they repeated the experiment with a higher overlap. Since participants were unaware of the study's true purpose and believed instead that the experiments were testing a newly acquired head-mounted display, we needed a way to determine if they perceived the redirection method used. To achieve this, participants were asked to verbally state during the experiments if they noticed anything unusual, and a message was displayed at the end of each trial asking "Have you noticed something unusual?". Based on the user's response, it was determined whether they actually perceived the redirection. The accepted answers for this experiment were as follows:

- The rooms are impossible.
- The wall separating the rooms shifted.
- The rooms expanded.

After finalizing the first experiment, participants were instructed to take a break while we set up the equipment for the next experiment. Before experiment two, we explained the participants that there would be a corridor in front of them with an ammunition box at the end. They were instructed to walk straight to the box, pick it up and walk back to the starting position. Participants began the experiment with translation gains set below one, specifically 0.75, 0.7, and 0.65. The initial trial was conducted with the gain set at 0.75. After completing this trial, participants were asked the adapted 2AFC question. Only if the participant did not perceive the redirection, the experiment continued with the lower thresholds. The following responses were considered as detection:

- I moved faster/slower in the VE than in the PE.
- The ammunition box seemed to move artificially closer/further from me.
- The walls seemed to artificially shift from/to me.
- I seemed to be moved artificially forwards/backwards.

Participants would then repeat the trial with translation gains set above one, specifically 1.4, 1.45, and 1.5. Upon completion of the second experiment, they filled out the questionnaires and received a debriefing about the true purpose of the study. This was followed by them answering the SSQ and RTLX [7]. The RTLX, an adaptation derived from the NASA Task Load Index [8], is a widely used tool for assessing the level of task load experienced by individuals. Finally, participants were asked to respond to additional questions and provide informal feedback.

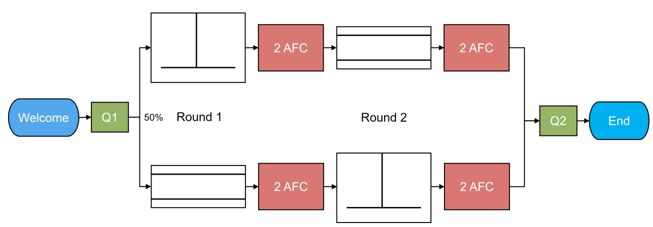


Figure 3: User study procedure for experiments 1 and 2 where distractors' effect on detection threshold is tested.

5 RESULTS

A total of 25 participants enrolled for the user study, consisting of 21 males and 4 females, with a mean age of 25.2 years (SD = 5.52). The Simulator Sickness Questionnaire (SSQ) scores did not show a significant change, indicating that the experiments did not induce severe cybersickness. Consequently, no participants were excluded. To assess the perceived task load, we calculated the mean RTLX scores for each question with the standard errors, including the total mean with standard error. The total mean of the RTLX scores is 2.62 (SD = 1.86). The mean RTLX score suggests that the VE, which includes the shooting distractor, does not impose a high task load on the user. This finding indicates that the inclusion of the shooting distractor in the VE does not significantly burden the participants with excessive cognitive demands.

5.1 Experiment 1

The answers collected from the adapted 2AFC questions were analyzed to determine the number of participants able to detect specific levels of overlap. The number of participants at each overlap level is cumulative, including those who detected lower levels of overlap. For example, eleven participants could detect 80% overlap, consisting of nine participants who could detect 65% overlap and two who detected 80% overlap. This is based on the obeservation that if a person is able to detect a particular level of overlap, they are likely to also detect it at a higher and more noticeable level of overlap. Interestingly, only eleven out of the total sample size (25), which is less than half, were able to detect the highest level of overlap. The percentage of participants detecting each level of overlap is depicted in Figure 4.

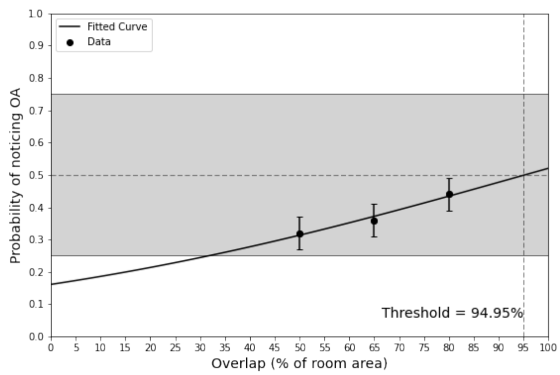


Figure 4: Detection results and standard deviation achieved in the OA experiment. The intersecting dashed lines indicate the absolute detection threshold.

The analysis revealed that none of the tested overlaps resulted in a detection probability exceeding 50%. Previous studies [23, 29] predominantly relied on generating a Sigmoid curve derived from the detection probabilities at each overlap level, with the threshold typically identified at a 50% probability of detection. However, our results, which demonstrated detection probabilities below 50% for all tested overlaps, suggest that the threshold cannot be precisely established under these conditions. Nonetheless, it is evident that with distractors and participants unaware of the experiment's purpose, considerably higher overlap levels are achievable, potentially up to 100%. The exact threshold cannot be pinpointed due to the insufficient data points available to accurately fit a Sigmoid curve, as illustrated in Figure 4, emphasizing that none of the values surpassed 50%.

5.2 Experiment 2

Similar to the OA experiment, the responses to the adapted 2AFC questions were analyzed and are shown in Figure 5. Participants are more sensitive to acceleration than deceleration in the VE. For gains less than 1, it was observed that only a gain of 0.65 was perceived by more than 50% of the participants. In contrast, for gains higher than 1, at gains of 1.45 and 1.5, more than 50% of the participants detected the redirection. Despite the limited data points, fitting the Sigmoid function and determining the 50% probability threshold was conducted. The primary objective is to demonstrate that higher threshold values (0.651 and 1.437) can be achieved with the use of continuous distractors while the user is in motion.

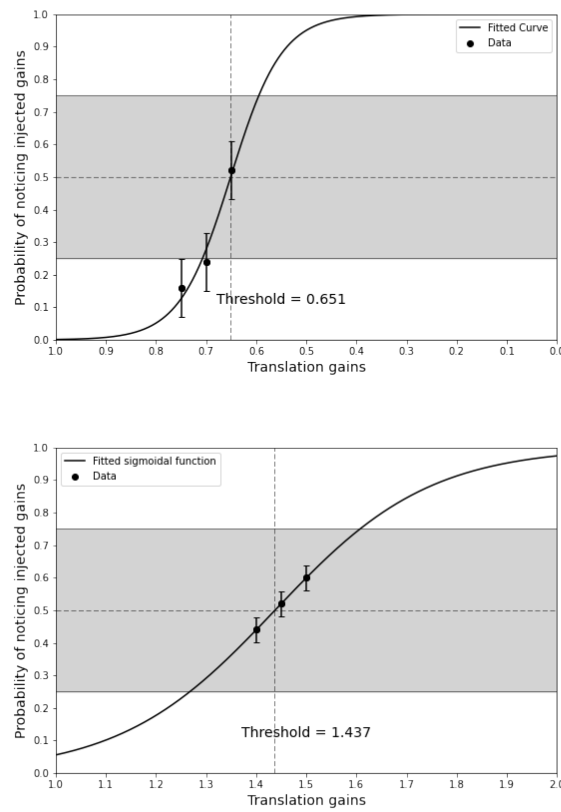


Figure 5: Results of translation gains tested in the RDW experiment. The intersecting dashed lines indicate the absolute detection threshold.

6 DISCUSSION

The results suggest that users engaged in a constant interactive task can be redirected at higher levels than those thresholds previously described in the literature. Room overlaps can reach up to 100%, while higher values can be used for translation gains. It is important to note that out of the 11 participants who noticed the room overlap, 7 had started with the RDW experiment and were thus able to perceive a redirection technique. This implies that awareness of environmental manipulation increases user attentiveness to anomalies, suggesting that the thresholds could potentially be even higher. However, this learning effect was not observed in participants who started with the OA and then proceeded to RDW, in terms of perceiving translation gains. Regarding the detection of translation gains, prior knowledge of RDW did not seem to help in its detection. Of the 15 participants who detected the 1.5 translation gain, 8 were aware of RDW and 7 were not, indicating that this previous knowledge was not a significant factor.

One limitation of this study is that the full range of overlaps and gains was not tested, potentially affecting the reliability of the perceived thresholds derived from the Sigmoid function. However, as preliminary work, it has been shown that the values are significantly higher than in experiments without distractors. For future studies, increasing the number of participants is recommended. Additionally, conducting the two experiments in separate sessions may help mitigate any potential learning effects. Regarding the overlap values to be tested, our results suggest that they could reach 100%, while for translation gains, the range should be expanded beyond what was examined in this study. Finally, we introduce a method to detect the perception of redirection without prior knowledge. However, the repetitive nature of the tasks and the repeated use of 2AFC questions could lead to increased attentiveness among users.

7 CONCLUSION

A key challenge in VR is the limited tracking space, which led to the development of redirection techniques to create the illusion of expansive VEs within physical constraints. This study introduces a novel approach by employing a common distractor while maintaining participants unaware of the redirection. The study comprises two experiments, one focusing on OA and the other on translation gains. Both experiments involve interactive tasks such as shooting balloons and collecting items, with participants' detection of anomalies assessed using adapted 2AFC questions.

The findings reveal a high redirection threshold for OA, reaching nearly 95%, indicating a low perception of overlap by participants. Regarding translation gains, thresholds below one are around 0.65, while for values above one, the threshold is approximately 1.43, indicating higher sensitivity. The study's limitations include a small participant pool and the potential bias introduced by repetitive questioning, which might have heightened participants' alertness to anomalies. In summary, this research enhances our understanding of OA and translation gains in VR, providing insights into optimizing limited tracking spaces. These limitations need to be addressed in future works. Moreover, we plan to investigate the use of indirect indicators, such as physiological responses or task performance metrics, for a more objective and reliable assessment of participants'awareness of the employed redirection.

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