Examining Rotation Gain in CAVE-like Virtual Environments

Sebastian Freitag, Benjamin Weyers, and Torsten W. Kuhlen

Abstract—When moving through a tracked immersive virtual environment, it is sometimes useful to deviate from the normal one-to-one mapping of real to virtual motion. One option is the application of *rotation gain*, where the virtual rotation of a user around the vertical axis is amplified or reduced by a factor. Previous research in head-mounted display environments has shown that rotation gain can go unnoticed to a certain extent, which is exploited in redirected walking techniques. Furthermore, it can be used to increase the effective field of regard in projection systems. However, rotation gain has never been studied in CAVE systems, yet.
In this work, we present an experiment with 87 participants examining the effects of rotation gain in a CAVE-like virtual environment. The results show no significant effects of rotation gain on simulator sickness, presence, or user performance in a cognitive task, but indicate that there is a negative influence on spatial knowledge especially for inexperienced users. In secondary results, we could confirm results of previous work and demonstrate that they also hold for CAVE environments, showing a negative correlation between simulator sickness and presence, cognitive performance and spatial knowledge, a positive correlation between presence and spatial knowledge, a mitigating influence of experience with 3D applications and previous CAVE exposure on simulator sickness, and a higher incidence of simulator sickness in women.

Index Terms—Rotation gain, virtual environments, virtual reality, CAVE, redirected walking, user study

1 Introduction

In a tracked immersive virtual environment, usually a one-to-one mapping between physical and virtual motion is used, allowing users to explore the virtual world by moving their head or walking. However, there are many cases where a deviation from this rule is necessary, mostly due to physical constraints of the system used (either a tracked lab space combined with a head-mounted display or a projection environment such as a powerwall or CAVE [11]). Using a one-to-one mapping, users can only travel in an area the size of the physical space, and, for projection systems, turn only in directions where screen surface is available.

The most common solution to this is the application of virtual travel techniques, where users navigate, for example, using a joystick or wand, or step in place [33]. However, it has been shown that traveling instead by means of *real walking* can lead to a higher sense of presence [41], superior performance in search tasks [31], more efficient travel [40], more accurate cognitive maps [32], and better results in cognitive tasks [26, 39, 48].

Redirection techniques can increase the size of the virtual space that can be traversed by real walking. In *redirected walking* [29], user movements and rotations are—usually imperceptibly—manipulated, for example by applying *gains*, to guide users away from physical boundaries and allow continuous walking. The most common manipulations are *translation gain*, where translational movement is amplified or reduced by a factor, *rotation gain*, where head rotations around the yaw axis are amplified or reduced by a factor, and *curvature gain*, where a rotation is induced based on forward translation, effectively leading the user to physically walk in a circle [35]. While translation gain alone can only enlarge the walkable area by a constant factor, rotation gain and curvature gain have the potential to allow almost infinite walking if the real space is large enough [8]. In addition, rotation gain can be used for redirection even in small areas (such as a CAVE), if enough turns are performed.

Redirection can also be performed by (usually less subtle) *reorientation* or *resetting techniques* [27, 45]. To prevent users from reaching system boundaries, these may freeze the simulation while the user is instructed to turn or move [45], or may enforce user turns within the travel interface [13]. Furthermore, reorientations can be performed by applying a rotation gain while users follow instructions to turn their heads [45] or look at a distractor [27, 28].

In addition to supporting redirection techniques, rotation gain can also be used to enlarge the effective field of regard (FOR) in large screen-based virtual environments (VEs) when no full 360° FOR is available, for example, to allow for more rotation in powerwall setups, or to compensate for a missing back wall in a CAVE [25].

However, although there are many possible applications for rotation gain, and although there have been numerous studies examining perceptual detection thresholds and effects of rotation gain in head-mounted display (HMD) setups, to our knowledge, the effects of applying rotation gain in CAVE environments have never been formally studied. Therefore, in this work, we present a between-participants study that examines effects of different magnitudes of rotation gain in a CAVE setup.

The rest of the article is structured as follows. Section 2 discusses related work analyzing the usability of rotation gain. In section 3, we formally define rotation gain and describe the implementation we used for this work, before section 4 examines considerations regarding the application of rotation gain in a CAVE. In section 5, we present the pilot study we conducted in preparation for the main study which is detailed in section 6. The main and secondary results of the study are presented in sections 7 and 8. Section 9 concludes the article and gives an overview of future work.

2 Related Work

For HMD setups, a body of work has examined effects and limits of rotation gain in virtual environments.

Noticeability An important limit of rotation gain is determined by detection thresholds, i.e., the magnitudes where most users start to notice that real and virtual rotation are not the same. In this context, Wallach found that healthy subjects perceive their environment as stable when it moves no more than 3% of the head turn in either direction [44], corresponding to rotation gain limits of 0.97 and 1.03. Jaekl et al. found that sitting participants who adjusted the rotation gain of their headset until it felt stable, accepted a wide range of rotation gains (68% of results between 0.84 and 1.41) [18], although the system had con-

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siderable latency (122 ms) and only 10 participants were examined. In a study with 9 participants and a simulated, seated HMD environment, Jerald et al. [19] gave conservative recommendations for limits of rotation gain of 0.923 and 1.022 and less conservative ones of 0.899 and 1.052, and note that the lower sensitivity to rotation gain < 1 may be supported by system latency. Engel et al. [12] tested 10 subjects and found detection thresholds of 0.85 and 1.35, also noting that all subjects found gains < 1 to be less comfortable. In an experiment with 12 subjects, Steinicke et al. found detection thresholds for rotation gains of 0.59 and 1.1 [36], and in a later study with 14 participants [37] thresholds of 0.67 and 1.24. In a study considering gender, Bruder et al. [9] examined 13 participants and found thresholds of 0.69 and 1.19 (men), and 0.66 and 1.25 (women), although the differences between the groups were not significant. Furthermore, Bruder et al. [6] found thresholds of 0.68 and 1.26 for standing and 0.77 and 1.26 for wheelchair-bound subjects, indicating that rotation gain can not only be used for upright users. In a study by Hodgson et al. [17], where rotation gains between 0.81 and 1.35 were used, a considerable number of participants (14 of 32) reported to have noticed some redirection (note, though, that other redirection techniques were used as well). Bolte et al. showed that rotation gain is less noticeable if it is only applied during eye saccades [4], establishing detection thresholds of a $5°$ scene rotation during a $15°$ saccade.

The variability in the results of previous work shows that different limits for rotation gain are regarded as acceptable. However, most studies indicate that a considerable amount of rotation gain is possible without most subjects noticing the manipulation.

Effects In addition to users noticing the manipulation, rotation gain can have effects on user performance. For example, Williams et al. found decreased performance in a pointing task when participants were treated with a strong rotation gain of 2.0 [45]. However, it is not clear if smaller gains can still lead to impaired spatial orientation. In a redirected walking experiment, Hodgson et al. [17] did not find any effect on error or latency in a pointing task when using moderate rotation gain (combined with curvature and translation gain). When examining verbal and spatial working memory tasks in an experiment with different *curvature* gains, Bruder et al. [7] found that with stronger redirection, participants performed significantly worse. Although curvature gain is different from rotation gain (rotating the scene when the users move instead of when they turn), comparable effects are conceivable for strong rotation gains, as well.

Due to the conflict between the visual and the vestibular and proprioceptive senses induced by the mismatch of real and virtual motion when rotation gain is applied, it is also possible that simulator sickness effects are increased [24, 30]. However, most previous research seems to suggest that there are at most small effects. In a series of experiments determining perceptual detection thresholds for translation, rotation and curvature gain [9, 36, 37], participants with high incidence of simulator sickness were invited again and tested without redirection. As they showed similar effects after a similar time, the authors concluded that the simulator sickness was not caused by the redirection. In two further experiments exploring redirected walking, the authors state that simulator sickness scores [20] after the experiment approximated results of previous studies involving walking in an HMD environment over comparable times without redirection [6, 7]. A different study had 3 of 21 participants abort the experiment due to simulator sickness when using translation, rotation and curvature gain [15], although the source of the cybersickness was not clear. Similar, but stronger effects were seen in a further experiment with translation, rotation and curvature gain, where 13 of 47 participants (32%) had to abort due to severe simulator sickness [16]. However, the authors do not regard this as a side effect of redirected walking, but just of the general VE experience, referring to previous studies without these effects.

Finally, LaViola et al. tested strong rotation gain in a three-walled CAVE-like environment as part of a travel interface to account for the missing back wall [25]. Although they did not study the effects, they note that with a rotation gain of 1.5, trial users experienced simulator sickness within a few minutes. However, they informally report a variant of the system with dynamic rotation gains based on the user's position in the CAVE to be usable.

In conclusion, it is not clear whether rotation gain or similar techniques have an effect on simulator sickness when applied within certain limits. While there are some insights given by previous work, to the best of our knowledge, there has not been a formal study examining the connection.

Although there have been numerous experiments establishing detection thresholds for rotation gain in HMD environments, there is little previous work regarding effects on spatial knowledge or orientation and cognitive load, or on a connection to presence or simulator sickness. Furthermore, CAVEs or other large projection systems have not been previously evaluated (Jerald et al. [19] used a projection system, but only to emulate an HMD and without users moving on their own, while LaViola et al. [25] used rotation gain in a CAVE, but did not evaluate). Therefore, in this work, we aim to fill this gap.

3 Rotation Gain Definition and Implementation

A rotation r can be described by a vector of three angles, indicating separate rotations around the pitch, yaw, and roll axes, i.e., $r = (r_{\text{pitch}}, r_{\text{yaw}}, r_{\text{roll}})$. When mapping a real-world head rotation r_{head} to a virtual camera rotation r_{virtual}, normally a one-to-one mapping is used, i.e., $r_{\text{virtual}} = r_{\text{head}}$. However, when applying a rotation gain, a factor $g = (g_{\text{pitch}}, g_{\text{yaw}}, g_{\text{roll}})$ is applied to the real rotation, i.e., $r_{\text{virtual}} = g \cdot r_{\text{head}}$, where $\cdot$ indicates element-wise multiplication. Similar to most related work (e.g., [6, 9, 15, 16, 17, 19, 35, 36, 37]), we only consider rotation gain around the yaw axis in this work, and use the convention that a rotation gain of α is shorthand for $g = (1, \alpha, 1)$.

Furthermore, we denote the magnitude of the manipulation induced by the rotation gain as its *gain strength*, defined as the absolute value of the *relative gain* describing the relative deviation from 1 (see [12]):

$$gain\_strength(gain) = \begin{cases} gain - 1 & : \quad gain \geq 1 \\ \frac{1}{gain} - 1 & : \quad gain < 1 \end{cases}$$

For example, the strength both of a gain of 1.12 and of its reciprocal value $1.12^{-1} = 0.893$ is 0.12.

We implemented rotation gain as a rotation of the virtual world around the user. In a CAVE, the virtual world normally (i.e., for a rotation gain of $\alpha = 1$) remains stationary relative to the CAVE during head rotations. For rotation gains of $\alpha > 1$, it instead rotates against the user's head rotation, for gains of $\alpha < 1$ with the head rotation. As this rotation is applied before any image is generated, technically, no additional delay is introduced. However, without rotation gain, there is essentially zero delay for head rotations in a CAVE, as the image on all walls remains largely unchanged (except for stereopsis). With active rotation gain, the image moves during head rotations and is therefore subject to the same delays as for head translations.

As the gain is only applied to yaw rotations, the axis of head rotation and the axis around which the rotation is amplified or reduced are not identical when the user is tilting their head, and become increasingly different the more a user looks up or down. Therefore, we do not apply rotation gain when the user's view direction (measured by head tracking) points up or down by more than $40°$. In order to avoid an effect of this on the study results, our study tasks are designed in a way that looking up or down happens only very rarely.

4 Considerations

The application of rotation gain can have different effects, depending on the intensity of the manipulation. Furthermore, these effects may be different in a CAVE than in an HMD setup. In this section, we outline which possible effects we expected, and discuss implications for the design of a study examining them.

An important effect that may be expected for strong rotation gain is *simulator sickness*, due to the mismatch between actual and visually perceived motion [24, 30]. As simulator sickness usually increases with longer exposure and can make a difference even after several days [22], a single participant cannot be tested for multiple rotation gain conditions, or only after a considerable break.

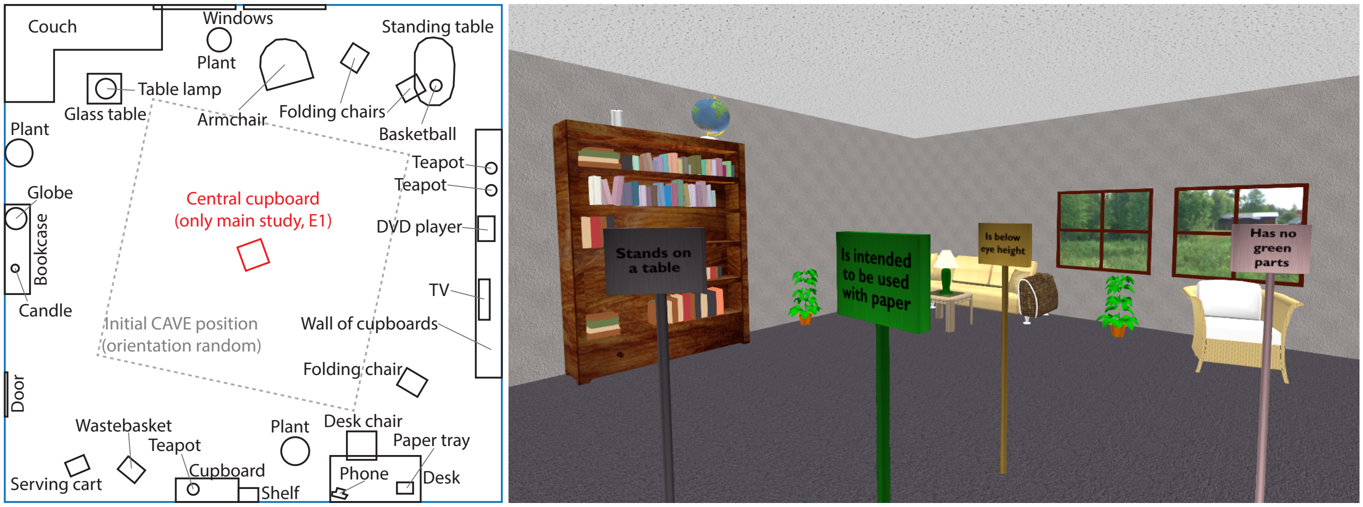

Fig. 1. **Left:** Schematic of the room used in both pilot and main study. The initial orientation of the CAVE area relative to the room was randomized at the beginning of each experiment to avoid possible effects caused by the (mis)alignment of real and virtual walls across conditions. **Right:** View of the puzzle task participants had to solve in the pilot study and experiment E2 of the main study. In the main study, the inscriptions on the signs were in German.

Further relevant effects include altered user performance (error rates, efficiency, cognitive load), impaired spatial knowledge and orientation, and effects on presence and subjective enjoyability.

Due to the complications regarding simulator sickness and expected learning effects, especially for user performance measures, we chose a between-subjects design, where each participant is only exposed to one rotation gain condition. This leads to the necessity of determining a discrete set of rotation gain levels that can be compared, which we did in a pilot study (see section 5).

Furthermore, the perception of rotation gain in CAVE environments can be expected to be different than in HMD setups. For example, in a CAVE, users can see their own body as a real world reference to the virtual stimuli. Furthermore, HMD screens always lag behind when users turn around, while a CAVE projection usually only changes very little. This can result in virtual worlds appearing less stable in general when presented in an HMD. In fact, when starting a head rotation, the image lag is similar to a rotation gain < 1, as the image seems to move slower than the actual motion [19]. Upon stopping the rotation, this lag has similar effects as a rotation gain > 1, as the image seems to move more than the user's head. These differences may mask possible effects of rotation gain manipulations in HMD setups, such that they can be expected to be more apparent in CAVE environments.

In contrast to several previous studies on rotation gain in HMD setups, we do not explicitly study the noticeability of rotation gain. This is due to the fact that in stationary screen-based setups, it is almost always possible to detect even weak rotation gains, as the (usually visible) system boundaries and the own body can be used as a reference. However, noticeability might not necessarily be the only or best estimator for applicability, as long as it does not negatively impact user performance, comfort or presence.

5 Pilot Study

To establish discrete rotation gain levels to compare in the main study, we conducted a pilot study among 16 virtual reality professionals (mean age 27.6, SD=3.8, 2 female). It was performed in a five-walled CAVE that provided a 360° horizontal field of regard, a $5.25\,\text{m}\times5.25\,\text{m}$ back-projected floor area, a height of 3.30 m, and a loudspeaker array on top. During the time in the CAVE, participants wore active stereo glasses operating at a frequency of 60 Hz per eye, tracked using ARTTRACK2 optical tracking at 60 Hz.

We tested 40 different rotation gains from the interval $[0.80; 1.19]$ in increments of 0.01. This selection roughly reflects previously established detection threshold results in HMD setups (see section 2), albeit within a smaller overall range, as we expected the effects to be more noticeable in a CAVE. Each participant was exposed to ten different rotation gains in random order, such that in total, there were 160 trials, testing each level four times. The scenario was an indoor environment where, in addition to furniture, several distinct objects, such as a basketball, a candle, or a wastebasket, were spread around a single room (see Fig. 1). This environment was chosen, as in an indoor scene, the user is always surrounded by (textured) scene geometry providing optical flow during movement and rotations, potentially leading to stronger vection. As effects such as simulator sickness can be expected to be stronger in scenarios inducing more vection [5], we suspect that they are easier to show in such an environment (compared to, e.g., a sparse outdoor scene). To accommodate for displacements occurring due to the application of rotation gain, the room was very large ($10\,\text{m}\times10\,\text{m}$).

The goal of the pilot study was to test the different rotation gain levels by evaluating them regarding their usability for real applications. Therefore, we chose a task that required some walking and turning around, as well as cognitive effort. As each of the ten gain levels per participant could only be tested for a short time, only expert users with considerable CAVE experience participated in the pilot study and were asked to extrapolate their experience to a prolonged usage.

The task consisted of a puzzle, where participants had to identify a target object in the room. To do this, they had to read four clues written on four signs placed in the room, that together uniquely determined the target object (cf. Fig. 1, right). When participants had read all clues and were certain of the correct answer, they selected the solution from a menu.

The signs were placed facing partly or completely away from the participant, such that walking and turning around was required to read all of them. As the scene was continuously displaced due to the application of rotation gain while walking, it regularly happened that signs were moved out of the CAVE area. Therefore, whenever a sign left the area reachable by walking, it disappeared into the ground and reappeared at a random position within the CAVE area (at least 1 m away from the participant). In these cases, the sign was again rotated such that the inscription was not readable from the participant's position.

Each trial for each rotation gain level consisted of two of these puzzles solved in succession, after which the participants rated their experience. They were asked to consider whether the effects possibly caused by the application of each level of rotation gain, when extrapo-

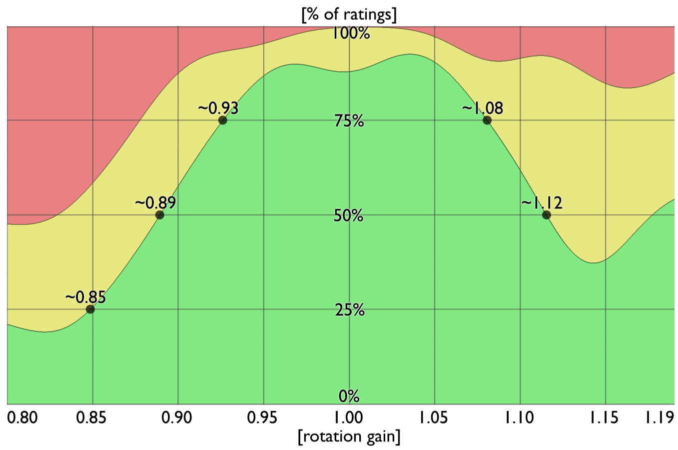

Fig. 2. Visualization of the (smoothed) ratings of the possible effects of the different rotation gain levels in the pilot study. Green corresponds to a *negligible*, yellow to a *tolerable*, and red to an *unfit for continuous use* rating. From the 75%, 50% and 25% quartiles of the *negligible* ratings, five gain levels were selected for the main study. As the 25% quartile is missing for gains > 1, we added 1.18 (the reciprocal of 0.85) as the sixth level.

lated to prolonged use, were *negligible*, *tolerable*, or made the setting *unfit for continuous use*. In total, including a training trial to ensure that the task was understood correctly, each participant spent between 20 and 30 minutes in the CAVE.

The results of the ratings are illustrated in Fig. 2, where green corresponds to a *negligible*, yellow to a *tolerable*, and red to an *unfit for continuous use* rating. For the visualization, a Gaussian smoothing ($\sigma = .02$) was applied to the ratings. The reason for this is that the results represent a discrete sampling of a continuous domain, where similar rotation gains can be expected to have similar ratings, such that the Gaussian smoothing accounts for the interpolation between the sampled points.

For the experimental conditions of the main study, we selected the rotation gain levels corresponding to the quartile thresholds—i.e., the 75%, 50% and 25% thresholds—of answers indicating a *negligible* effect both for gain levels < 1 and > 1 (cf. Fig. 2). This selection was made, as we expected measurable effects in the main study for the levels where only 25% of experts saw no more than a negligible impact of rotation gain, small effects at the half-way point, and no effects where at least 75% of experts judged the effects as negligible.

However, while the impact of effects judged by the experts seemed to increase with stronger rotation gain, the results seem to indicate a decrease for rotation gains beyond 1.14, such that the 25% threshold does not exist for gains > 1. This could either be a real effect or an artifact due to the limited number of participants. However, as the 75% and 50% thresholds for gains < 1 and > 1 were symmetrical w.r.t. their reciprocal value (cf. [12]), we added the reciprocal of the 25% threshold for gains < 1 (i.e., $0.85^{-1} \approx 1.18$) as sixth experimental condition.

This selection resulted in the levels (rounded to two decimal places) 0.85, 0.89, 0.93, 1.08, 1.12, and 1.18, where 1.00 (no gain) was used for the control group. Note that the selected thresholds are largely independent of the Gaussian smoothing applied to the data beforehand (for $\sigma \in [0.01; 0.03]$).

6 Study

We conducted a study to establish possible effects of rotation gain in CAVE environments and to determine its applicability regarding user comfort and performance. Due to the reasons outlined in section 4, it was a between-participants experiment, testing the six gain levels determined in the pilot study against a control group (rotation gain 1.0).

The study took place in the same CAVE system as the pilot study (see section 5). As participants were always alone in the CAVE, they were supervised the whole time using cameras and microphones by an examiner who could also answer using the loudspeakers. In the second experiment (see section 6.1.2), participants additionally carried a wireless presenter remote to confirm choices.

6.1 Procedure

The study consisted of two experiments. The main goal of the first experiment (E1) was to examine whether different rotation gain levels have an influence on the spatial knowledge of users. In the second experiment (E2), we tried to find out whether rotation gain imposes additional cognitive load on users. In both experiments, we looked for effects of rotation gain on simulator sickness, presence and subjective task load. During both experiments, the rotation gain level was always the same. Rotation gain was always active, except when participants looked up or down by more than 40° (see section 3). However, this almost never happened due to the nature of the tasks ($< 0.3\%$ of the time). At the beginning of both tasks, the virtual room was rotated randomly to avoid possible effects due to specific (mis)alignments of real and virtual walls.

First, participants were informed about the general procedure of the study, including a short description of how a CAVE works, and gave their informed consent. Afterwards, they filled out a short demographic questionnaire and Kennedy's simulator sickness questionnaire (SSQ) [20]. Subsequently, they completed both experiments followed by accompanying questionnaires (see sections 6.1.1 and 6.1.2). Each experiment was preceded by detailed written instructions, whereupon all remaining questions were answered. After the experiments, a concluding questionnaire asking about the overall experience in both (e.g., enjoyability) was filled out. Furthermore, it included questions whether participants had noticed certain effects, for example, if the virtual world had rotated, blurred, appeared unstable, changed size or vibrated. The main reason for this was to find out whether naïve participants would notice the rotation in the different conditions, while most of the other questions were decoy questions. Finally, participants were briefed about the purpose of the study. In total, the procedure took 73 minutes on average (SD=10.5 min) per participant from start to finish.

6.1.1 Experiment E1

The main goal of the first experiment was to determine whether different levels of rotation gain have an influence on spatial knowledge, an effect that has already been demonstrated previously in an HMD environment using pointing tasks and strong rotation gain [45]. We assessed this by examining the subconscious cognitive map build-up. In order to simulate a realistic usage scenario containing walking, turning, and looking around, we used a search task as primary assignment. The task took place in the environment already used in the pilot study (see section 5 and Fig. 1, left). In addition, a cupboard with shelves at eye height on all four sides and a footprint of 50 cm$\times$50 cm was placed in the center of the room. In order to successfully complete the search tasks, participants had to walk around and look into it from different sides.

In each trial of the search task, 50 small objects were randomly distributed around the virtual room (cf. Fig. 3) and in the central cupboard. There were six different object types that were easy to distinguish (mug, trophy, bottle, can, soap dispenser, flowerpot). In addition, all objects were inscribed with a large letter (A, B, C, or D). The goal of the task was to find a specific target object with a specific letter, that only existed once in the room (e.g., a mug inscribed with the letter B). However, participants were not told the target object directly. Instead, four possible target objects were shown in large picture frames placed on the walls of the virtual room. Only one of these, the actual target object, actually existed in the room (the other three were used as decoy), such that participants had to look around frequently to find the correct target object. When they had found it, they verbally stated its inscription letter and where they had found it. Then, the room faded out and in again, the room's center was moved to the CAVE's center to account for possible displacements due to the rotation gain (cf. Fig. 1, left), and a new search task trial began.

Fig. 3. View of the search task participants solved in experiment E1.

As the target object, the position of objects, and the decoy targets shown in the picture frames were chosen randomly, trials could be perceived as differently difficult. For example, participants could find the target object after a few seconds or only after searching for a while, depending on the arrangement and where they looked first. However, as the task was used primarily to ensure that participants moved, turned, and looked around, while their success was not important, this is not a problem for the task design.

The first trial was used for training, i.e., participants could still ask questions that were answered by the examiner. After exactly 10 minutes, the experiment ended and participants left the CAVE, independent of how many trials they had completed. This time span includes the training trial to ensure that the exposure time remained identical for all subjects, since effects such as simulator sickness often increase with time.

After the experiment, participants filled out Kennedy's SSQ [20], the SUS presence questionnaire [42] and the NASA-TLX subjective task load questionnaire [14]. Then, they were asked to draw a top view of the virtual room they were in, including all objects they remembered in their proper locations. If they did not remember the location of an object, they were asked to enter it into a list. They were told not to draw or mention any of the search task objects, nor the cupboard or the picture frames used in the search task, but to include all of the furniture and interior decoration. Afterwards, they were given a complete list of all objects actually contained in the room, and asked to draw another map with the same instructions. This was done to allow a differentiation of whether participants had general trouble remembering objects, or were only uncertain about their location in the room. For both map drawings, graphical quality was not important and participants were asked to label the objects to avoid ambiguity. It is important to note that participants were not told about the map drawing before the search task to avoid that they consciously memorized the contents of the room.

6.1.2 Experiment E2

The goal of the second experiment was to examine whether active rotation gain imposes an additional cognitive load on users. For strong *curvature gain* in an HMD environment, a negative effect on performance in cognitive tasks has already been shown [7], but it is unclear whether this transfers to rotation gain in a CAVE. To examine this, we used two verbal tasks that participants had to perform simultaneously.

The first task was the puzzle task already used in our pilot study (section 5), solved in the same room (cf. Fig. 1). However, to avoid interruptions and effects of user interaction, the solution to the puzzle was not selected from a menu, but just spoken aloud, whereupon the examiner pressed a corresponding button. Furthermore, as stronger rotation gain induces more positional drift, the signs with the clues are moved out of the walkable area more frequently in the conditions with stronger gain. Therefore, the number of sign movements was enforced artificially, by moving one of the signs at random whenever there had been fewer sign movements than one every 7 seconds since the beginning of the experiment. This value was determined empirically to be above any expected number of repositionings with some tolerance, such that the total number of sign movements was approximately equal for all participants and all rotation gain levels, including the control condition. When an answer was spoken aloud, the environment faded out and in again with a new puzzle, and the room's center was moved back to the CAVE's center. Participants were not told whether their answer was correct. Again, the first puzzle was used for training, and participants could ask questions that were answered by the examiner.

For the second simultaneous task, audio recordings of words were played back to participants once every 5 seconds, similar to [39]. They had to decide as fast as possible whether the word fit the category *body parts/organs*, and if so, press a button on the carried presenter remote. Thus, we could measure the error rate and reaction times for words in the category. The category was chosen as it is familiar to most people and includes a large variety of common words.

To prepare this task, we compiled a list of 62 well-known German words from the category *body parts/organs* and 72 words which are not in the category. This list was then given to 20 native speakers independently, who decided whether each word belonged to the category or not, and indicated when they thought the classification was ambiguous, the word could be misunderstood, or a word might be unknown. We then discarded all words where more than 10% categorized a word differently than the majority, or noted any of the problems mentioned above. This left 26 words from the category (e.g., "finger", "nose", or "muscle"), and all 72 other words, of which we selected 26 that had the same number of syllables as the words from the category (e.g., "Monday", "cheese", or "tennis"). After having a native speaker record these 52 words, they were played back in random order to 20 further native speakers who had to decide for each word whether it belonged to the category or not. As not a single word was misclassified by any of them, we concluded that the categorization is unambiguous and the audio recordings well understandable, and used them for the experiment (word list and audio recordings are available upon request).

After 10 minutes, the experiment ended and participants left the CAVE. Again, this included the training puzzle, to keep the time of exposure identical for all subjects. Participants then filled out Kennedy's SSQ [20], the SUS presence questionnaire [42] and the NASA-TLX subjective task load questionnaire [14].

6.1.3 Hypotheses

Based on our pilot study and findings of previous work, we expected the following results of the study:

H1: Simulator Sickness Participants will report more simulator sickness in the 0.85 condition than in the control group, as in our pilot study, only 25% of experts expected non-negligible effects at this level. Based on estimates in previous work with HMDs [6, 7, 9, 15, 36, 37], we do not expect simulator sickness effects at the other levels.

H2: Spatial Knowledge In the strong rotation gain conditions, we expect worse map drawing results than in the control condition, even though the gain levels used in the study are below the ones used in previous work [45].

H3: Cognitive Load Participants will perform worse in the strong rotation gain conditions in experiment E2, similar to [7]. However, the effects may be small, since in [7], very strong curvature gain was used.

6.2 Participants

In total, 87 participants (17 female, 70 male, mean age 25.7, SD=6.6) took part in the study, who were recruited using different sources (internet forums, public postings, word-of-mouth). As an incentive, six cash prizes (4×25€, 2×50€) were awarded to six random participants. 35 subjects (6 female, 29 male) had used a CAVE system before (most of them only for a short time, e.g., in campus demos). No participant had used a CAVE for more than two hours within the last three years, and none worked professionally in a field related to virtual reality. 38 people reported to use 3D applications on a computer (e.g.,

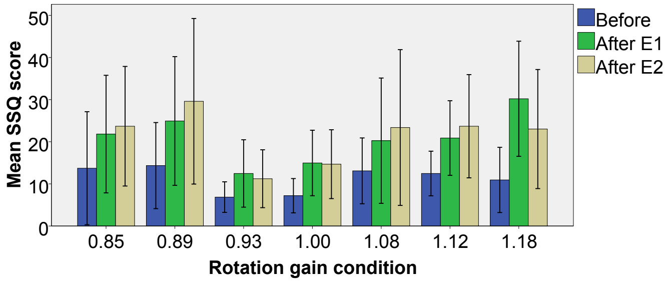

Fig. 4. Simulator sickness (SSQ) scores before the study and after experiments E1 and E2 by rotation gain condition. The error bars indicate 95% confidence intervals.

CAD software or video games) at least once a month. The participants were distributed into one of the seven conditions randomly, counterbalancing for gender and whether they had CAVE experience. All participants were naïve to the purpose of the study. One participant (in the 0.85 condition) had to abort the experiment during E2 due to severe simulator sickness and thus provided only partial data (measured results and questionnaires from E1 were used, but not from E2 or the concluding questionnaire). For another one (in the 0.89 condition), the word classifications in E2 were not logged due to a technical problem. All participants were fluent in German, which was required to ensure that results did not vary due to language skills.

7 Main Results

As main results, we looked for effects of the rotation gain *condition* on different variables. We analyzed the results with a one-way ANOVA at the .05 significance level, using Welch's ANOVA instead where Levene's test indicated that the assumption of homogeneity of variances was violated. Post-hoc Dunnett's tests were used to compare the results of all experimental conditions against the control condition (gain 1.0). Futhermore, we looked for Pearson correlations between the rotation gain *strength* (see section 3) and different variables. Note that a correlation between the gain strength and another variable only shows a general linear trend between the application of rotation gain and that variable, and does not allow to determine a threshold level above which the effect becomes relevant. In addition, effects may not be symmetrical w.r.t. the rotation gain, i.e., there may be different effects for gains <1 and >1. Throughout the paper, we report *significant results* at the .05 level and *non-significant trends* at the .1 level.

7.1 Subjective Measures

We measured a mean simulator sickness (SSQ) score of M=11.0 (SD=12.6) before the experiments, a mean score of M=21.1 (SD=19.4) after E1 and M=21.3 (SD=22.2) after E2, indicating a moderate increase of simulator sickness over the time of the experiment (cf. Fig. 4). An ANOVA revealed no significant main effect of the condition on SSQ scores after E1 ($F_{6,80}$=1.20, p=.313) or E2 ($F_{6,79}$=.95, p=.465). There was a trend for a positive correlation between gain strength and SSQ scores after E1 (r=+.182, p=.092), but not after E2 (p=.143).

The mean SUS score for the sense of feeling present in the VE was M=4.45 (SD=1.04) after E1 and M=4.56 (SD=1.03) after E2, which indicates a high sense of presence [42]. An ANOVA revealed no significant main effect of the condition on presence after E1 ($F_{6,80}$=.25, p=.976) or E2 ($F_{6,79}$=.33, p=.947). There were no significant correlations between gain strength and presence (p>.5).

The mean score for subjective task load (NASA-TLX) on a scale of 0 to 100 was M=41.3 (SD=16.5) for E1 and M=58.1 (SD=25.4) for E2. An ANOVA revealed no significant main effect of the condition on subjective task load for E1 ($F_{6,35.33}$=1.10, p=.383) or E2 ($F_{6,79}$=.953, p=.462). There were no correlations with gain strength (p>.6).

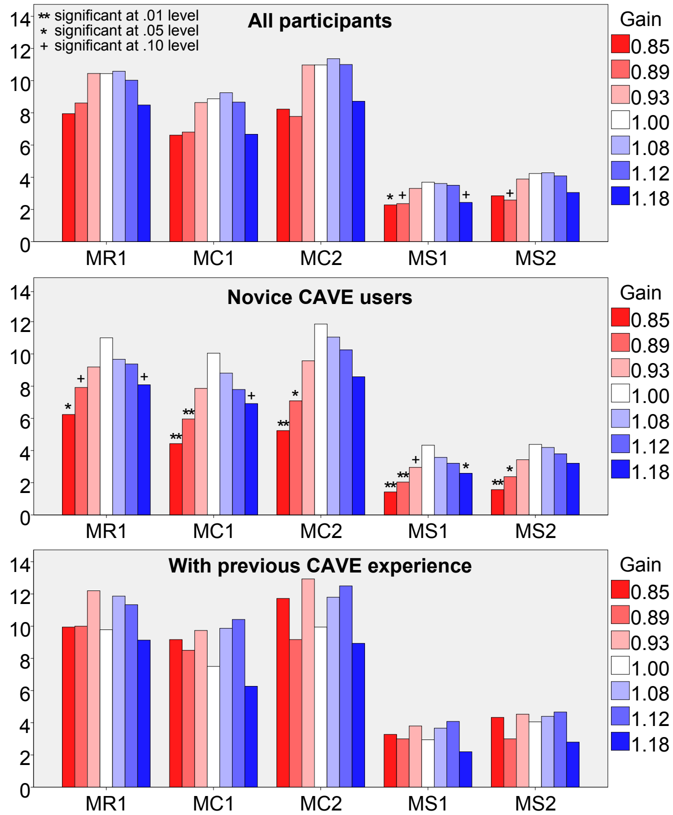

Fig. 5. Map drawing results for all participants, as well as only novice and experienced CAVE users, showing the number of remembered objects (MR1), the number of correctly placed objects in the first (MC1) and second (MC2) drawing, and overall scores for both drawings (MS1/MS2). Significant differences to the control condition (gain 1.0) are marked.

7.2 Spatial Knowledge

From each participant, we obtained two map drawings—the second of which was drawn with the help of a list of all objects contained in the room—as well as a list of objects the participant remembered when sketching the first map, but did not know where. To evaluate their correctness, all of them were given to three reviewers who were blind to the participants' experimental condition. Each reviewer determined five ratings for each participant:

MR1: The number of objects the participant had remembered (ignoring their placement) in the first map and the list,

MC1: The number of (approximately) correctly placed objects in the first map,

MS1: An overall score for the quality of the first map, ignoring drawing quality, but considering incorrectly placed or made-up objects and the accuracy of placement, on a scale of 0 (totally wrong or empty map) to 10 (correct representation including details), similar to [3] and [38],

MC2: The number of correctly placed objects in the second map,

MS2: An overall score for the quality of the second map.

For the evaluation, the ratings of all reviewers were averaged. An overview of the mean values for the different conditions is given in Fig. 5. An ANOVA revealed no significant main effect (however, a trend) of the condition on MR1 ($F_{6,80}$=2.13, p=.059), MC1 ($F_{6,80}$=1.93, p=.085) and MC2 ($F_{6,80}$=2.18, p=.053). Furthermore, we found significant main effects on MS1 ($F_{6,80}$=2.76, p=.017) and MS2 ($F_{6,80}$=2.50, p=.029). Results of follow-up Dunnett's tests are visualized in Fig. 5. Moreover, we split the participants by whether

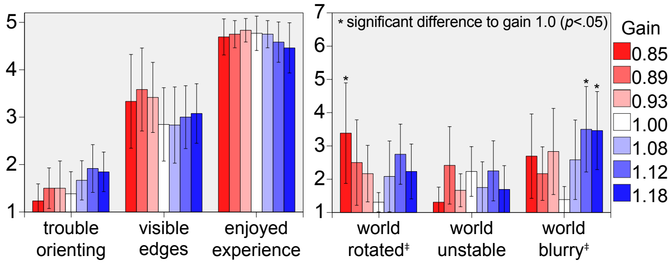

Fig. 6. Mean ratings of questionnaire items. The error bars denote 95% confidence intervals. **Left:** Ratings on a 5-point Likert scale (1: *strongly disagree*, 5: *strongly agree*) of the statements *"I had trouble orienting myself"*, *"The CAVE's edges were clearly visible"* and *"I enjoyed the experience"*. **Right:** Ratings on whether participants had noticed certain effects on a scale of 1 (*not at all*) to 7 (*very noticeable*) for *"The virtual world rotated"*, *"The virtual world appeared unstable"* and *"The virtual world was blurry at times"*. Significant differences to the control condition (gain 1.0) are marked by *, correlations with gain strength by ‡.

they had used a CAVE before. Within the group of novice users, we found significant main effects of the condition on MR1 ($F_{6,45}$=3.22, p=.010), MC1 ($F_{6,45}$=4.36, p=.001), MC2 ($F_{6,45}$=4.38, p=.001), MS1 ($F_{6,45}$=5.91, p<.001) and MS2 ($F_{6,45}$=4.11, p=.002) (details in Fig. 5), and significant negative correlations between gain strength and all of these values ($-.554 \leq r \leq -.428$, p<.001).

For participants with previous CAVE experience, there were no significant effects or correlations.

7.3 Task Performance and Behavior

In E1, there was no significant main effect of the condition on the average task completion times ($F_{6,80}$=.963, p=.456). We did not evaluate the error rate, as only 7 participants made a mistake. In E2, there were no significant main effects of the condition on puzzle answer error rates ($F_{6,79}$=.79, p=.578) and answer times ($F_{6,79}$=.77, p=.593), nor on word classification reaction times ($F_{6,78}$=.53, p=.787). There was a trend for word classification error rates ($F_{6,78}$=1.92, p=.088), but post-hoc tests were not significant.

As a measure of user behavior, we compared the total amount of rotation around the vertical axis that participants performed physically and in the VE. ANOVAs revealed significant main effects of the condition on the physical and virtual rotation in E1 ($F_{6,80}$=4.73, p<.001 and $F_{6,80}$=6.08, p<.001) and E2 ($F_{6,34.72}$=3.52, p=.008 and $F_{6,79}$=2.99, p=.011). Follow-up Dunnett's tests showed that in E1, subjects turned on average 19% less in the VE in the 0.85 condition (p=.007) compared to the control group. Furthermore, they physically turned 16% less in the 1.12 condition (p=.036) and 17% less in the 1.18 condition (p=.020). In E2, post-hoc tests were not significant.

7.4 Questionnaires

We evaluated whether participants had noticed certain effects (on a scale of 1=*not noticeable at all* to 7=*very noticeable*) as part of the concluding questionnaire. For the question of whether the virtual world had rotated, an ANOVA revealed a significant main effect of the condition ($F_{6,33.21}$=4.09, p=.004). Follow-up Dunnett's tests showed that in the 0.85 condition, subjects had given a significantly higher mean score (M=3.39, SD=2.50) than in the control condition (M=1.31, SD=.48, p=.010). Moreover, there was a positive correlation between rotation gain strength and the scores (r=+.288, p=.007). Furthermore, for the question of whether the world had become blurry at times, an ANOVA revealed a significant main effect of the condition ($F_{6,33.85}$=4.60, p=.002). Follow-up Dunnett's tests showed that in the 1.12 and 1.18 condition, subjects had rated significantly higher (M=3.50, SD=2.02 and M=3.46, SD=1.94) than in the control condition (M=1.39, SD=.65, p=.019 for both). In addition, the scores for this question correlated positively with gain strength (r=+.270, p=.011). Moreover, we asked whether participants had enjoyed the experience (on a 5-point Likert scale), which was ranked very high on average (M=4.69, SD=.60). An ANOVA showed no significant differences between conditions ($F_{6,80}$=.56, p=.762), nor did we find a correlation with gain strength (p=.224). Further detail can be found in Fig. 6.

7.5 Discussion

The results of the experiments show no significant influence of the different levels of rotation gain on presence or reported simulator sickness, contrary to hypothesis H1. In addition, we could not observe an effect on user performance in a cognitively challenging task (contrary to H3) or in the self-reported subjective task load, nor on subjective enjoyability. This suggests that rotation gain—within the range of $[0.85; 1.18]$ as tested in the experiment—can be used in a CAVE environment in practice without causing physical discomfort, diminishing the realism of the experience, or inducing additional cognitive load. However, as there was a trend for a positive correlation between rotation gain strength and SSQ scores after the first experiment, there may be a small effect of rotation gain on simulator sickness. Further research is necessary to determine whether this is a real effect and if so, for which levels of rotation gain it occurs. Furthermore, it should be examined whether the effect is stronger for longer exposure times, which may limit the usability of stronger rotation gain, or whether users adapt to the condition, diminishing the effect after some time.

Furthermore, even though there was a positive correlation between rotation gain strength and the reported noticeability of the rotation, most participants still rated the noticeability as low (cf. Fig. 6). Although it is always possible to detect rotation gain in a CAVE as long as system boundaries or body parts can be used as a reference, it was apparently not conspicuous enough to be strongly noticed by most naïve participants.

It has to be noted, though, that participants only spent 2×10 minutes in the CAVE. Some effects might only occur after a longer exposure. Furthermore, participants in the strong gain conditions (especially for the levels 0.85 and 0.89) performed worse on the map drawing tasks, indicating an inferior spatial knowledge as predicted in hypothesis H2. However, this phenomenon occurred predominantly for first-time CAVE users and could not be observed for participants with any previous CAVE experience. A possible explanation for this is that strong rotation gain might have a small effect on spatial knowledge that is only visible in people who are simultaneously becoming accustomed to the virtual reality experience for the first time. Returning users, on the other hand, already know the experience and can adapt to the manipulated rotation without suffering a detrimental effect on their spatial abilities. However, novice users also suffered from more simulator sickness (see section 8.2). As there is some indication that simulator sickness correlates negatively with the performance on spatial knowledge tasks [2], this could be an alternative explanation.

Participants also reported that the world had occasionally blurred more often in the experimental conditions, especially for stronger rotation gain (cf. Fig. 6). This effect can probably be explained by the fact that in contrast to the control condition without active rotation gain, the image on the CAVE walls moved during head rotations. However, as the ratings by most participants were low (indicating low noticeability), and they did not perform worse on the experimental tasks, more research is necessary to determine whether this effect might, e.g., reduce the readability of text or diminish user performance in other tasks.

Furthermore, the results show that participants physically turned less for rotation gains of 1.12 and 1.18 in E1, indicating that they adapted to the rotation gain and could effectively use it to save physical effort. On the other hand, with a rotation gain of 0.85, participants turned significantly less virtually than in the control group in E1, although it would seem reasonable that the virtual rotation would be the same in all conditions, as the task was always the same. This indicates that participants avoided the additional physical rotation necessary for the same virtual rotation, which possibly makes effective redirection harder to realize using this gain level.

	Female M (SD)	Male M (SD)	*p*
before the study	8.4 (9.0)	11.7 (13.4)	.334
after E1	27.1 (23.1)	19.6 (18.4)	.159
after E2	31.8 (24.7)	18.9 (21.2)	**.036***

Table 1. Differences between the incidence of simulator sickness (SSQ scores) reported by female and male participants.

The fact that post-hoc tests on altered rotation are not significant in E2 is probably due to the nature of the task being less planned, faster-paced, and more demanding cognitively, which may have slowed down adaptation to the rotation gain.

We could not observe an effect of rotation gain on performance in a cognitively challenging task, contrary to the indication of a connection given by Bruder et al. [7]. However, in their experiment, very strong curvature gain was used (clearly above detection thresholds [6, 9, 36, 37]), while we used rotation gains close to detection thresholds (for HMD setups) in our experiment. This indicates that cognitive effects only occur when the inconsistency between the visual and the proprioceptive and vestibular senses is too large.

In conclusion, we could not confirm our hypotheses H1 and H3, as we could not find significant effects on simulator sickness or cognitive load. Furthermore, our hypothesis H2 predicting worse results on a spatial knowledge task in stronger gain conditions is only confirmed for first-time CAVE users. Instead, the results suggest that rotation gain can effectively be used in CAVE environments within the range of $[0.85; 1.18]$ without clear negative effects on user comfort or performance (at least for people who have used a CAVE at least once before). Possible restrictions include slightly higher ratings for noticeability and perceived blurriness in the experimental conditions as well as limited physical compensation for the reduced virtual rotation for a gain of 0.85. However, more research is needed to confirm these results, especially regarding longer exposure times and possibly stronger rotation gains.

8 Secondary Results

As secondary results, we looked for effects of gender, of whether subjects had used a CAVE before, and of experience with 3D applications on different variables, which was possible as these variables were counter-balanced across conditions. We compared these values using independent samples t-tests (Welch's t-tests), correcting the degrees of freedom when Levene's test indicated that the assumption of homogeneity of variances was violated. Additionally, we examined Pearson correlations between different variables in the experiment.

8.1 Gender Effects

We found significant differences in simulator sickness scores between female and male participants, summarized in Table 1. However, there were no significant differences regarding gender in all other variables.

8.2 Effects of CAVE and 3D Experience

Mean SSQ scores for simulator sickness after both experiments, based on whether subjects had used a CAVE at least once before and on whether they use 3D applications at least once per month showed significant differences, summarized in Table 2. There were no significant differences in presence based on CAVE or 3D experience.

The mean evaluations of map drawings, based on whether participants had used a CAVE before, showed significant differences, summarized in Table 3. Values based on usage of 3D applications are omitted for brevity, as there are no significant differences.

8.3 Correlations

In experiment E1, simulator sickness (SSQ) correlated negatively with presence (SUS) and performance on map drawing tasks. Furthermore, in E2, we found a positive correlation with error rates in both simultaneous tasks. In addition, simulator sickness correlated positively with

	N	SSQ after E1 M (SD)	*p*	SSQ after E2 M (SD)	*p*
CAVE_before					
Yes	35	15.2 (11.7)	**.009***	15.0 (12.2)	**.015***
No	52	25.0 (22.6)		25.4 (26.3)	
3D_apps					
Yes	38	15.0 (11.6)	**.005***	16.5 (12.3)	.060+
No	49	25.8 (22.9)		25.0 (27.4)	
First-time CAVE users: 3D_apps					
Yes	15	13.0 (12.3)	**.002***	16.7 (13.3)	**.045***
No	37	29.9 (24.1)		28.9 (29.4)	

Table 2. Reported simulator sickness (SSQ) scores based on whether subjects had used a CAVE at least once before (*CAVE_before*) and on whether they use 3D applications at least once per month (*3D_apps*).

	Yes M (SD)	No M (SD)	*p*
remembered objects (MR1)	10.6 (2.9)	8.8 (2.5)	**.003***
map 1: corr. placed obj. (MC1)	8.7 (3.3)	7.4 (2.8)	**.046***
reviewer score (MS1)	3.3 (1.6)	2.9 (1.3)	.208
map 2: corr. placed obj. (MC2)	11.0 (4.0)	9.1 (3.5)	**.020***
reviewer score (MS2)	4.0 (1.8)	3.3 (1.6)	**.048***

Table 3. Map drawing evaluations based on whether participants had used a CAVE before.

subjective task load (NASA-TLX), and negatively with reported enjoyability in both experiments. In E1, presence scores (SUS) correlated positively with the performance on map drawing tasks. In both experiments, presence correlated positively with reported enjoyability. Detailed results can be found in Table 4.

Furthermore, we analyzed correlations between presence and the performance on map drawing tasks based on whether participants had used a CAVE before (see Table 5). For users with previous experience, we found a stronger positive correlation, while there was no significant correlation for novice users (p>.4 for MR1, p>.9 for MC1, MC2, MS1 and MS2).

8.4 Discussion

The secondary results discussed in this section are independent of the rotation gain condition. However, it has to be noted that 74 of the 87 participants were in the experimental groups (with some rotation gain), such that it cannot be excluded that some effects may occur differently without rotation gain. Nevertheless, as most of the presented results are in accordance with effects already reported in previous work, and the rotation gain condition did not seem to have an effect on most variables, we believe that the generalization to other scenarios is sound.

Our results show a significantly higher incidence of reported simulator sickness in female subjects. This is not an effect of previous experience, as the ratio of women was equal in both the group of first-time CAVE users and the group that had already used a CAVE before. As this effect has already been observed previously [21, 23, 34], our results are consistent with previous work and expectations. It has to be pointed out, however, that more research is necessary to find out why this might be the case. In our particular case, the result could also be due to women and men reacting differently to the perceptual inconsistency introduced by rotation gain [43]. However, we did not have enough female participants to examine this possibility more closely, as most of them were in the experimental groups.

Furthermore, we found significant effects of previous CAVE usage and experience with 3D applications (cf. Table 2). People who used a CAVE for the first time reported a significantly higher incidence of simulator sickness. Similar findings apply to participants who use 3D applications less than once a month. The highest incidence of simulator sickness is found in people that neither use 3D ap-

correlations in experiment E1		r	p
SSQ	*presence (SUS)*	$-.225$	**.037***
	remembered objects (MR1)	$-.217$	**.043***
	map 1: corr. placed objects (MC1)	$-.248$	**.020***
	reviewer score (MS1)	$-.188$	.081$^+$
	map 2: corr. placed objects (MC2)	$-.209$	.052$^+$
	reviewer score (MS2)	$-.208$	.054$^+$
	post-questionnaire: map drawing easy	$-.243$	**.024***
	subjective task load (NASA-TLX)	$+.225$	**.037***
	post-questionnaire: enjoyability	$-.381$	**.000***
SUS	*remembered objects (MR1)*	$+.270$	**.011***
	map 1: corr. placed objects (MC1)	$+.189$	.079$^+$
	reviewer score (MS1)	$+.229$	**.033***
	map 2: corr. placed objects (MC2)	$+.221$	**.040***
	reviewer score (MS2)	$+.221$	**.039***
	post-questionnaire: map drawing easy	$+.312$	**.003***
	post-questionnaire: enjoyability	$+.343$	**.001***

correlations in experiment E2		r	p
SSQ	*presence (SUS)*	—	.112
	error rate: puzzle answers	$+.287$	**.007***
	error rate: word classification	$+.238$	**.028***
	subjective task load (NASA-TLX)	$+.285$	**.008***
	post-questionnaire: enjoyability	$-.300$	**.005***
SUS	*post-questionnaire: enjoyability*	$+.377$	**.000***

Table 4. Correlations between different variables in both experiments, especially simulator sickness (SSQ) and presence (SUS). The post-questionnaire items were only rated once at the end of the study.

correlations with SUS score in E1	r	p
remembered objects (MR1)	$+.435$	**.009***
map 1: corr. placed objects (MC1)	$+.352$	**.038***
reviewer score (MS1)	$+.458$	**.006***
map 2: corr. placed objects (MC2)	$+.436$	**.009***
reviewer score (MS2)	$+.439$	**.008***

Table 5. Correlations between presence (SUS score) in E1 and performance on map drawing tasks for participants who had used a CAVE at least once before the experiment. For novice users, none of the correlations are significant ($p > .4$).

plications often nor had used a CAVE before. These findings are consistent with previous results showing that simulator sickness effects are significantly reduced after more exposures to a VE (even for the second time) [1, 10, 20]. Furthermore, we found that participants who had used a CAVE before performed significantly better on a spatial knowledge task (map drawing), remembering more objects and placing more objects correctly (cf. Table 3). It is notable that there are no similar results based on experience with 3D applications, which means that previous CAVE usage actually has an effect on spatial abilities in the VE (even for the comparatively little experience of most of our participants). These findings have important implications on the design of user studies in CAVE systems, underlining that if participants include both novice and experienced users, they have to be balanced across experimental conditions. In addition, novice users could receive a training with the VE on a separate occasion before the experiment to reduce variability in the results.

The results show that incidence of simulator sickness correlates negatively with presence, which is consistent with previous work [46, 47]. Furthermore, it is positively correlated with error rates and subjective task load responses, and negatively with reported enjoyability and map drawing success, which is also in accordance with previous findings [2, 23, 47]. Note that these correlations are not solely due to CAVE experience (novice CAVE users had generally higher error rates and SSQ ratings than returning users), as similar correlations can be found within the group of novice users, and the reported enjoyability did not differ based on experience. These results underline that the avoidance of simulator sickness is critical for the quality of the immersive experience.

Furthermore, presence correlated positively with reported enjoyability, although it is unclear whether this is actually an effect of presence, or if it is due to the connection between presence and simulator sickness. Moreover, there is a positive correlation between presence and spatial knowledge (measured by map drawing success), which has also been found before [2]. Closer analysis revealed that there is a strong correlation within the group of users with previous CAVE experience, but no connection for novice CAVE users (cf. Table 5). There are several possible explanations for this difference. Novice users performed significantly worse on map drawing tasks in stronger rotation gain conditions (see section 7.2), indicating that they needed more effort to adapt to the altered environment conditions, which may have masked any advantages of presence. In contrast, users with previous CAVE experience show no decreased performance due to rotation gain, as they were able to adapt to it, allowing for the positive effect of presence on spatial knowledge [2] to dominate. However, it is also possible that the missing effect of presence in novice users is not (or not exclusively) caused by their lack of experience, but may be due to the generally higher incidence of simulator sickness or other variables in that group. Nevertheless, in both cases, this result emphasizes the importance of increasing presence, especially if spatial information from the experience should be remembered afterwards (such as in training scenarios).

In conclusion, our secondary results provide additional evidence that simulator sickness has a negative influence on a wide range of variables, including presence, perceived difficulty, actual user performance and comfort, but occurs less severely for users with previous 3D or CAVE experience, and is reported less strongly by male users. In addition, we see a positive effect of presence on the performance in a spatial knowledge task.

9 Conclusion

In this article, we presented an experiment in which we evaluated possible effects of rotation gain in a CAVE-like virtual environment. We could find no significant evidence of rotation gain having a detrimental effect on simulator sickness, presence, enjoyability or user performance in a cognitive task within the range we examined, although there is some indication that for stronger rotation gains, there may be an effect on simulator sickness. Even though there was a negative influence on spatial knowledge for stronger rotation gain levels, the effect mainly occurred for participants using a CAVE system for the first time. Our findings suggest that rotation gain within the range of $[0.85; 1.18]$ can be employed for use in CAVE environments.

For future work, other redirection techniques that have already been successfully used in HMD setups (especially translation and curvature gain) should be examined in a CAVE environment. Furthermore, more research is necessary regarding user comfort and performance during significantly longer times of exposure to redirected walking techniques in a CAVE. Moreover, the reasons behind the different effects of previous CAVE experience on the influence of rotation gain and on simulator sickness that we found have to be more clearly studied.

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