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Perception Thresholds for Unobtrusive Movement in VR Versus AR

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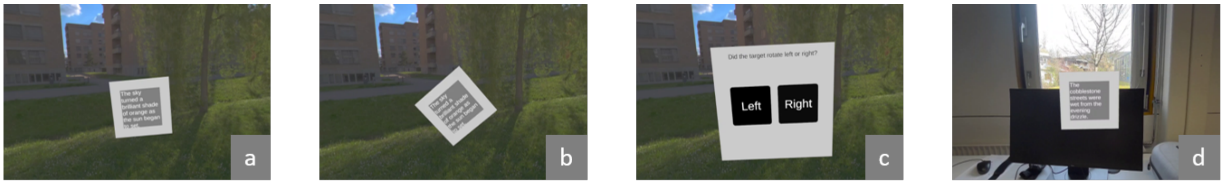

Figure 1: Task for rotation around the z-axis (RZ): (a) The text-display starts to move. (b) It moves for five seconds (the movement is exaggerated here to make it visible). (c) An answering slide prompts the user to decide if the display rotated left (counter-clockwise) or right (clockwise). (d) The real environment is visible in the AR condition, while (a) to (c) show the virtual environment.

Abstract

Over the last years, extended reality (XR) has been actively promoted as a tool for productivity or office tasks instead of purely for entertainment. Unfortunately, technical limitations of head-mounted XR devices could cause additional ergonomic problems to the ones that office workers already face, such as back pain caused by prolonged sitting. A possible countermeasure that XR offers is to adjust the workplace by placing virtual screens anywhere without physical restrictions. Previous work has also proposed to subtly move screens in VR to induce movement and active sitting in the users without distracting them from their tasks. We replicate a study on perception thresholds for such subtle movement in VR and extend it to AR. Our results mostly confirm those previously documented in VR and that similar effects can be observed in AR.

Index Terms: Unobtrusive Movement, Virtual Reality, Augmented Reality, Replication

1 Introduction

Extended reality (XR), including augmented reality (AR) and virtual reality (VR) devices, has recently been actively promoted for knowledge work because they can, for example, provide unlimited display space in any situation. Unfortunately, XR devices suffer from health and ergonomic issues, such as the weight and pressure on the face [3, 1]. On top of that, there are problems that already exist in conventional office settings in which workers suffer back pain or hypertension caused by prolonged sitting [21, 5]. Therefore, it is prudent to explore the ergonomic advantages afforded by XR over a standard desktop setup, such as virtual screens and windows that can be placed effortlessly in any position. In addition, previous research in human-computer interaction has proposed a variety of solutions on how systems could encourage users to fix their posture or be more active during their workday, both in a purely physical environment and in XR [22, 11].

While such interventions may benefit health, they may also interrupt users' focus on their work. Therefore, Shin et al. [28, 27] suggested moving the screen unobtrusively to induce small movements in the user without distracting them from their work. First, they tested this approach in the physical world with a screen attached to a robot arm [28]. Then, they conducted a study in VR to identify perception thresholds for a slowly moving virtual screen, once for continuous movement, and once for larger displacements during eye blink [27]. Our study focuses on continuous movement, a baseline technique that can be used with any head-mounted display (HMD), even without eye-tracking capabilities. More specifically, we are replicating and verifying the perception threshold study for continuous movement in VR using a newer HMD with a significantly higher resolution. As most current-generation headsets also enable video-passthrough augmented reality, which might be preferred by knowledge workers in certain tasks (to be aware of their surroundings), we extend the study beyond the original work by determining the threshold in video see-through augmented reality. We are therefore conducting a partial replication as defined by Hendrick [8]. Consequently, a main contribution of this work is a discussion of the differences between VR and AR results.

2 Related Work

Prior research has shown that prolonged sitting without active breaks can cause problems such as lower back pain [21] and is associated with exhaustion, decreased job satisfaction, hypertension, and musculoskeletal disorder symptoms [5]. To mitigate possible health effects caused by prolonged sitting, prior research has looked at how to detect sitting behaviors and give feedback to improve posture [15]. This paper is not concerned with the detection of sitting posture. Instead, we are interested in unobtrusively enticing users to adopt a better sitting posture or engage in more active sitting. Previous research has explored incentivizing users to change their posture actively through simple pop-up windows that show the user how to adjust their posture [10], a device at the neck that vibrates if the neck posture is unhealthy [14], or vibrotactile feedback that directs users towards certain positions [33]. Other approaches use gamification, such as showing an illustration of how to improve sitting posture next to a score and leaderboard [22], by taking care of a virtual pet through pose adjustments [20], or by a virtual flower providing posture feedback [9]. Research has also looked at how the infrastructure can contribute to a healthy posture, for example, by automatically adjusting the computer monitor, desk, and chair positions [32] or the height of the desk [17]. In addition, a successful system needs to avoid disturbing the user's work, and Haller et al. [7] found that physical feedback was rated less disruptive than graphical or vibrotactile feedback.

Some prior work on ergonomics has also focused specifically on XR. Evangelista et al. [6] proposed a system that visualizes the interaction cost for each reachable position in a virtual space, focusing mainly on arm fatigue. Cheng et al. [4] proposed interactions with enhanced ergonomics by including input modalities that rely

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on physical objects such as haptic feedback and resting platforms. Ji et al. [11] compared visual and auditory real-time feedback methods for posture adjustment and found they could reduce the time spent in uncomfortable positions. XR also has the unique potential to improve ergonomics in the workplace by adapting the position of virtual screens [24], while new input modalities, such as eye gaze and spatially tracked input devices [2], could be instrumental in supporting the posture of users. Finally, the immersive qualities of XR can help improve the user's general well-being, reducing stress [25] or distractions [26] through environment customization.

However, XR also introduces new problems that add to the conventional health problems encountered in the office. In a review of the literature, Souchet et al. [29] found five risks of working in VR, including cybersickness, visual fatigue, muscular fatigue, acute stress, and mental overload. During a one-week study, Biener et al. [3] found that wearing a VR device can be uncomfortable and decrease well-being compared to a standard workplace. Users were also often adjusting their HMD [1], especially less experienced users, who were more easily distracted. In addition, using XR can lead to increased head movement [19], potentially intensifying problems with the neck or shoulders. Kazemi et al. [12] argue that there is a disproportional amount of research relating to cybersickness, visual fatigue, mental workload, performance, spatial presence, and usability compared to research on physical workload, posture, stress, and discomfort. They emphasize the importance of methods to increase health and well-being at work. Therefore, we replicate and extend an experiment reported by Shin et al. [27], who proposed to exploit change blindness, i. e., the inability to detect visual changes, to induce subtle changes to the screen arrangement. The goal of Shin et al. [27] was to slowly move the virtual screens to induce movement in the users without them noticing. They conducted their experiment in VR, which affords fine-grained control over the entire range of visual stimuli to determine the detection threshold at which users start noticing that the screen is moving. We are partially replicating this experiment with a current headset and extending it to video-see-through AR, which is currently promoted for office and knowledge work by devices such as the Apple Vision Pro[1].

3 Method

We mainly followed the experimental procedure of the first experiment described by Shin et al. [27]. The main differences in our study are the addition of an AR condition and the use of a new HMD with significantly higher resolution than in the original study.

3.1 Task

Participants were presented with a virtual screen that changed position and orientation at different rates, defined by an offset in millimeters or degrees per second. The study was divided into six phases to evaluate movement along each of the six degrees of freedom separately (Figure 2). We will refer to these movements with their abbreviations throughout the rest of the paper: translation along the x-axis (TX), translation along the y-axis (TY), translation along the z-axis (TZ), rotation around the x-axis (RX), rotation around the y-axis (RY), and rotation around the z-axis (RZ). During screen movement, participants were asked to read the text on the screen. After the screen moved for five seconds, the text display was hidden by an answering slide, and participants were prompted to choose the previously shown movement in a two-alternative forced-choice task (2AFC). They had to choose between opposite movement types, such as left/right, up/down, or clockwise/counterclockwise. If they did not know the correct answer, they were instructed to guess it. This process is depicted in Figure 1.

[1]https://www.apple.com/uk/apple-vision-pro/

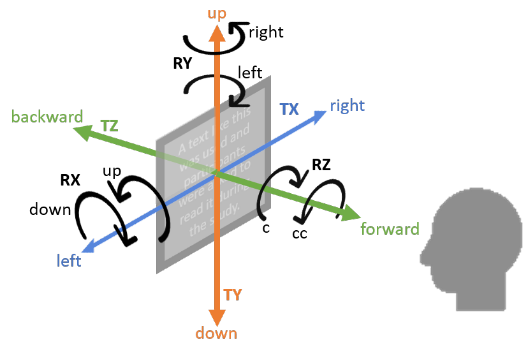

Figure 2: Movement directions that were tested: translation in the x-direction (TX), in the y-direction (TY), and z-direction (TZ), as well as rotation around the x-axis (RX), y-axis (RY), and z-axis (RZ).

3.2 Apparatus

We used the Meta Quest 3 with a resolution of 2064×2208 pixels per eye. This headset has a much higher resolution than the HTC Vive Pro that was used in the original study (1440×1600 pixels per eye). Similarly, the field of view of the Quest 3 (110° horizontal, 96° vertical) is larger than that of the HTC Vive Pro (110° diagonal). The frame rate of our study application was set to 90 Hz, as in the original study. The application was built using Unity 2022.3.34f1 and deployed as a standalone application. The position and size of the virtual screen were set according to ergonomic guidelines described in the original study, to size of 73 cm × 73 cm, at a distance of two meters, at a 6° downward angle from the user's eyes. Following the original study, we placed a 49 cm × 49 cm gray square on the virtual screen and set the font size so that six lines of text in a san-serif font fit into the square. We used short AI-generated sentences. This setup is depicted in Figure 1. The virtual environment only included the virtual screen and a panoramic background image, as can be seen in Figure 1. For the AR condition, participants were placed in front of an office desk with a computer and a view out of the window into nature, as is visible in Figure 1(d).

3.3 Procedure

First, participants completed a consent form, a demographic questionnaire, and the simulator sickness questionnaire [13]. After the participants put on the HMD, they were instructed to adjust the inter-pupillary distance to their ideal setting. The six phases of the experiment were counterbalanced using a balanced Latin square. Half of the participants started with AR and completed all six phases before continuing with VR, and the other half started with VR. Exactly as described by Shin et al. [27], the task was explained to the participants in the beginning, and they were told there was no right or wrong answer, meaning that they should guess in case they did not know. At the beginning of each phase, participants could press a button to adjust the screen's position to the height of their eyes. To ensure that the participants understood the task, they performed six training tasks for each phase, for which the movement of the screen was exaggerated and which was repeated until all answers were correct. In each task, the virtual screen moved at a constant speed for five seconds. We tested ten different offsets, or movement speeds, which were directly adopted from the original study [27]. For translations in x and y direction these ranged from -2.5 mm/s (movement to the left/down) to 2.5 mm/s (movement to the right/up) in steps of 0.5 mm/s. For translations in z direction they ranged from -4.25 mm/s (forward movement) to 4.25 mm/s (backward movement) in steps of 0.85 mm/s. For rotations in x and y direction, the offsets ranged from -0.9 degrees/s (downwards or right movement) to 0.9 degrees/s (upwards or left movement) in steps of 0.18 degrees/s. For rotations in z direction, they ranged from -0.198 degree/s (clockwise movement) to 0.198 degrees/s (counter-clockwise movement) in steps of 0.044 degrees/s. The offsets can be seen on the x-axis of the results in Figure 3. Within each phase, the order of the different speeds was chosen randomly, but each speed occurred exactly three times. These three repetitions were applied both in the VR and the AR condition, so that the overall number of repetitions matches the one used in the original study, which had six repetitions only in a VR condition. This experimental design was required to ensure that the overall duration of the study did not become too long. After all phases (both in AR and VR) were completed, the participants removed the HMD and completed the simulator sickness questionnaire [13] again.

3.4 Participants

Overall, 12 university students and employees (8 female, 4 male) participated in the study. Their mean age was 26.1 years ($sd = 3.5$). Three people wore glasses during the study. Only two people had no prior VR or AR experience.

3.5 Analysis

Since we only collected three trials per participant and offset, we pooled the responses of all participants to calculate the probabilities of detecting a "positive motion" for each offset. The directions right (TX), up (TY), backward (TZ), up (RX), left (RY), and counter-clockwise (RZ) were considered positive motions. If the positive motion is very clearly noticeable, the probability should be 100%; if the negative motion is very clearly noticeable, the probability should be zero. If the movement is not easily perceivable and participants are simply guessing, we would expect a probability of 50%. Standard errors for each offset were calculated as a Bernoulli distribution ($\frac{1}{n}\sqrt{p \cdot (1-p)}$, with the number of all trials n). After calculating the probabilities, we fitted a psychometric function to our data using R [18] while selecting a logistic function of the form: $1/(1+e^{-\beta*(x-\alpha)})$. Thresholds were set to 25% and 75% in line with prior work [27, 30, 16].

4 Results

In the following, we present the results of our study and compare them with the original study's findings by Shin et al. [27]. The raw data from our study, as well as the apps for running the study can be found under: https://osf.io/xzy65/?view_only=3e6e966b1d0a4a9aa95fe30465418802

4.1 Simulator Sickness

The mean simulator sickness recorded before the study was 9.35 ($sd = 16.76$). After the study, we measured it to be 26.8 ($sd = 21.62$). While the value before the experiment was only slightly lower compared to the original study (m=11.22, sd=8.22), it was notably less than the value reported by Shin et al. [27] (m=40.51, sd=34.98) after completion of the study. This difference could be explained by the variability between participants. It could also be caused by the use of a different VR device, or because users in our study were spending half of the study in AR, which could induce fewer symptoms.

4.2 Thresholds in VR

The detection thresholds varied between movement types and movement directions. Our data indicates that participants were slightly more susceptible to translations in the right, up, and forward direction than to translations in the left, down, and backward direction. In general, translations at a speed below 0.677 mm per second were undetected in any direction.

For rotations, the data indicates that participants were more susceptible to upward rotations (around the x-axis), right rotations (around the y-axis), and clockwise rotations than to the corresponding opposite rotations. In addition, participants were much more susceptible to rotations around the z-axis than to rotations around the x-axis and the y-axis.

4.3 Comparing VR Results to Original Study

The thresholds for both our VR condition and the original study are visualized in Figure 3. The numbers can be easily compared in Table 1. Shin et al. [27] report that, regardless of the direction, translations of the virtual screen can remain undetected for speeds below 0.6 mm per second, which is very close to the threshold of 0.677 mm from our study. As in the original study, we also found that participants were least sensitive to the backward translation. The original study found the forward translation to be the second least sensitive. In our study, however, the sensitivity of this motion was within the scope of the translations in x- and y-direction. While the original study reported that upward translations were less visible than downward translations, the opposite was true for our study. Yet, both ours and the results of the original study indicate that left and backward translations are less visible than their counterparts.

Regarding rotations, we could confirm the findings of the original study that the participants were much more sensitive to rotations around the z-axis than to rotations around the x-axis or y-axis. Both our data and the data from the original study showed that participants were slightly more susceptible to right rotations (around the y-axis) and clockwise rotations than the corresponding opposite rotations. However, for rotations around the x-axis, participants in the original study seemed more susceptible to downward rotations, while our participants found upward rotations slightly more visible.

4.4 Comparison between VR and AR

The AR results can be seen in Figure 4, together with the thresholds from our VR study. The values can be compared with both VR studies in Table 1.

The data indicates that translations at a speed of below 0.416 mm per second were undetected in any direction. This is considerably lower than the overall threshold measured for VR, which was 0.677 mm per second (0.6 mm per second in the original study). Similar to the original study's results, the forward and backward translations were the least noticeable. However, in our AR study, the forward translation was the least noticeable, while the backward translation was the most noticeable for both VR studies. Just as in our VR study, the downward translation was less visible than the upward translation in our AR study, which contradicts the results from the original study. The AR data also indicates that the right and forward translations are less visible than their counterparts, while the opposite was true for both VR studies.

Regarding rotations in AR, participants were much more sensitive to rotations around the z-axis, as has already been seen in both prior VR studies. However, while both VR studies indicated that participants were more sensitive to right (around the y-axis) and clockwise rotations, the AR data showed the opposite, that participants found left and counter-clockwise rotations more visible. For rotations around the x-axis in AR, the upward rotation seemed to be more visible, as has also been found in our VR study.

5 Discussion

The group of participants in our study and the original study consisted of university members. For both, the mean age was in the mid-twenties, three people wore glasses, and ten participants had prior XR experiences. However, our group of participants contained slightly more female participants (67%) than in the original study (50%). Overall, the selection of participants is very similar and, therefore, can only validate prior findings but not generalize them to other demographic groups.

Overall, the results of the original VR study and our VR condition do not show very pronounced differences. The minimum threshold for undetected translations is in the same range for both

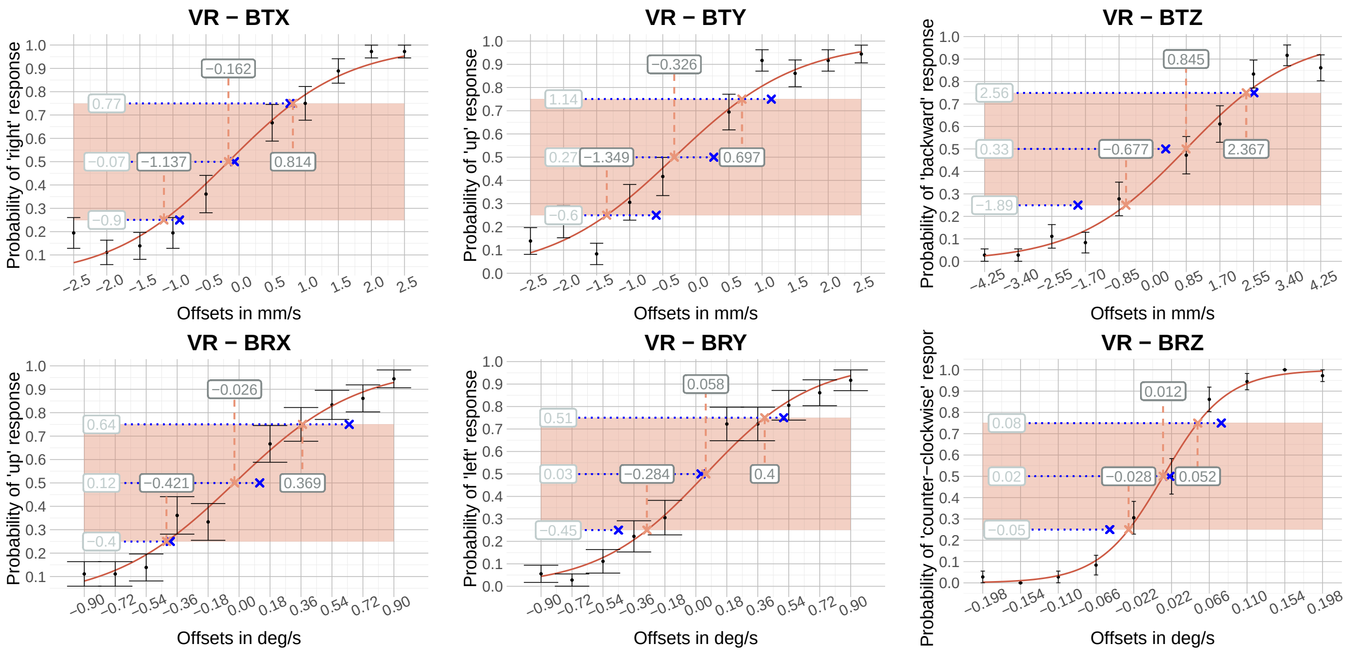

Figure 3: VR results: The x-axis shows the offset in millimeters and degrees per second. The y-axis displays the corresponding probabilities for a positive movement. The orange line is the fitted psychometric function. The area within the thresholds (25% and 75%) is marked in light orange. Thresholds are indicated with an orange X. For comparison, the values of the original study are marked in blue.

Table 1: Threshold values of the original study for VR, and our study in both VR and AR.

	TX			TY			TZ		
Thresholds	VR orig. [27]	VR	AR	VR orig. [27]	VR	AR	VR orig. [27]	VR	AR
$p = 0.25$	-0.9 mm/s	-1.137 mm/s	-0.468 mm/s	-0.6 mm/s	-1.349 mm/s	-0.883 mm/s	-1.89 mm/s	-0.677 mm/s	-1.78 mm/s
$p = 0.5$	-0.07 mm/s	-0.162 mm/s	0.111 mm/s	0.27 mm/s	-0.326 mm/s	-0.234 mm/s	0.33 mm/s	0.845 mm/s	-0.122 mm/s
$p = 0.75$	0.77 mm/s	0.814 mm/s	0.690 mm/s	1.14 mm/s	0.697 mm/s	0.416 mm/s	2.56 mm/s	2.367 mm/s	1.536 mm/s
	RX			RY			RZ		
Thresholds	VR orig. [27]	VR	AR	VR orig. [27]	VR	AR	VR orig. [27]	VR	AR
$p = 0.25$	-0.4 deg/s	-0.421 deg/s	-0.483 deg/s	-0.45 deg/s	-0.284 deg/s	-0.441 deg/s	-0.05 deg/s	-0.028 deg/s	-0.053 deg/s
$p = 0.5$	0.12 deg/s	-0.026 deg/s	-0.099 deg/s	0.03 deg/s	0.058 deg/s	-0.027 deg/s	0.02 deg/s	0.012 deg/s	-0.002 deg/s
$p = 0.75$	0.64 deg/s	0.369 deg/s	0.285 deg/s	0.51 deg/s	0.400 deg/s	0.388 deg/s	0.08 deg/s	0.052 deg/s	0.048 deg/s

(original VR: 0.6 mm per second, our VR: 0.677 mm per second). The results suggest that, in our VR condition, the movement was slightly less visible, with the minimum threshold allowing 12.8% more movement per second. We speculate that the increased resolution of the Quest 3 may result in smoother movement, making it less noticeable.

Both VR studies showed that participants were least sensitive to backward translations, which are movements away from the user. In our VR condition, the threshold for backward translations was around 3.5 times higher than the lowest translation threshold and for the original study [27] it was even more than four times as high as the lowest translation threshold. This could be explained by the fact that a translation of a certain step size in the x- or y-direction covers a much larger degree of the user's field of view than the same translation in the z-direction. For example, moving the screen 0.6 mm to the right changes the position of the right edge of the screen by 0.0167°, yet, moving the screen by 0.6 mm to the back changes the position of the right edge of the screen by only 0.003°. However, it is surprising that, while the thresholds for backward translation are very similar in both, our VR condition indicated a much lower threshold for forward translations than the original study.

Both the original VR study and our VR condition agree that left- and backward translations are less visible than their counterparts. It could be speculated that left translations are less visible because the left movement actually supports the reading by moving letters towards the user's current point of gaze.

For rotations, both VR studies showed that users are more sensitive to rotations around the z-axis than to the other two axes. Again, this could be explained by the smaller angular change when rotating around the x- or y-axis, or because humans might be more susceptible to changes on a 2D plane perpendicular to the line of sight.

In both VR studies, participants were more susceptible to right- (around the y-axis) and clockwise rotations than to opposite rotations. Again, the reason could be that the text is moving away from the user's gaze point, and more effort is needed from the user to catch up. Following that reasoning, downward rotations (around the x-axis) and downward translations should be more visible, as shown in the original VR study, which was surprisingly the opposite in our VR condition. This observation could be due to noise in the data or indicate that the directionality of the task does not play such an important role after all. A study with a much larger participant pool would be needed to clarify this.

The overall threshold for undetected translations was found to be considerably lower in our AR condition, around 39% lower, than in our VR condition. We assume that this could be due to more background details in the AR environment. On the other hand, a similar study by Wang et al. [31], in which the authors identified thresholds for size discrimination, indicated that size differences were harder to perceive in AR than VR. In contrast to both VR studies, the backward movement was more visible than the forward movement in

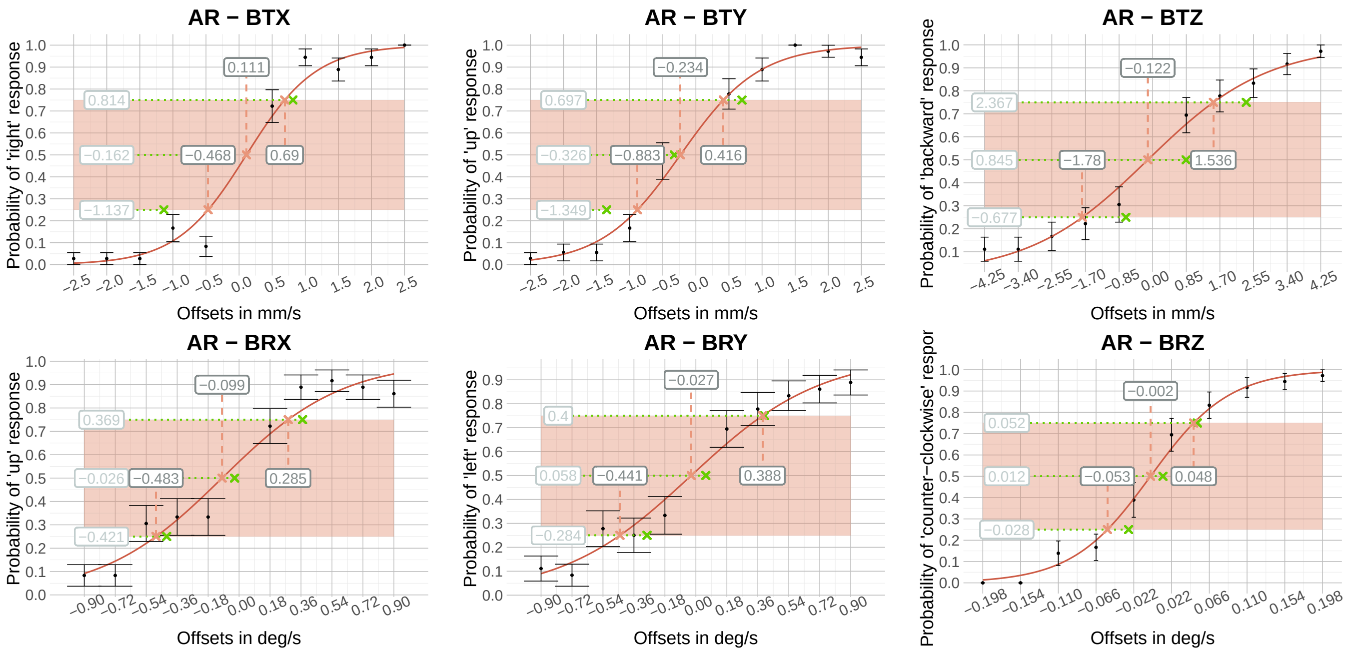

Figure 4: AR results: The x-axis shows the movement speed in millimeters and degrees per second. The y-axis displays the corresponding probabilities for a positive movement. The orange line is the fitted psychometric function. The area within the thresholds (25% and 75%) is marked in light orange. Thresholds are indicated with an orange X. For comparison, the values of our VR study are marked in green.

AR. However, the difference between the two directions was less prominent than in VR. In AR, the right and forward translations seem less visible, while the left and backward translations are less visible in both VR studies. This could further indicate that the task's directionality does not play a significant role.

For rotations, the AR results were in line with both VR studies, in which rotations around the z-axis were much more visible than other rotations. Yet, in AR, left (around the y-axis) and counter-clockwise rotations were more visible, while both VR studies found that right (around the y-axis) and clockwise rotations were more visible. For rotations around the x-axis, AR was in line with our VR condition in that upward rotations were more visible, contrasting the findings of the original VR study. This also contradicts the theory that the threshold is influenced by the reading direction.

In summary, we replicated a prior study and tested the generalizability of prior findings to new conditions as proposed by Nosek and Errington [23]. In our case, the new condition is AR. We can mostly confirm the findings of Shin et al. [27], except for some minor differences. In addition, we found that the thresholds differed slightly more for the AR condition. We speculate that the differences between the two VR studies and our AR study could be due to the display resolution and the fidelity of the displayed background. We also observed differences in the absolute thresholds between opposite movement directions, which could arise from the directionality of the reading task. However, as our results did not always match the results of the original study in this regard, it remains unclear how strong this effect is.

Our results confirm the range of speeds at which virtual content can be moved without the user noticing. Besides inducing movement during prolonged sitting, these measures could also be useful in other domains, such as unobtrusively shifting the user's attention in immersive videos and games, educational settings, or for guided data exploration.

5.1 Limitations and Future Work

In our VR condition, we only collected half as many datapoints as in the original study, because we distributed the tasks between VR and AR while keeping the study at a reasonable length. Future studies should extend the participant pool further or separate the AR and VR parts to get more data points. In addition, the age range of participants in our study, and the original study [27], was limited. A greater age range should be considered in future studies to also consider the effect of age on the perception threshold.

While the original paper [27] also determined the threshold for sudden movements during eye blinks, we only focused on replicating and extending their first experiment. In addition, they explored the effect of moving the virtual content on posture change, performance, and subjective responses. We did not replicate this part, but future studies should evaluate the effect of moving the virtual content on the users' posture more closely, especially for long-term use in ecologically valid settings.

Another limitation is that we can only make assumptions about the cause of the varying perception thresholds for the different movements. The visual backgrounds in our VR and AR conditions were different, which likely influenced the resulting thresholds, yet it is unclear to what extent. Additional studies would be needed to investigate this more closely, testing a range of different backgrounds. In addition, different display resolutions should be evaluated and other tasks than reading should be tested, because directionality might affect how visible movements in certain directions are. One could also repeat the reading task using a language with another reading direction. If a systematic effect of the different backgrounds can be confirmed, we could leverage this property in future applications by adapting the speed based on the environment.

Unfortunately, we cannot compare our results to the robot arm study [28], as different metrics were used. Yet, it would be interesting to compare our results with the ground truth in a physical setting where the movement is not influenced by the resolution of a display.

6 Conclusion

We present a partial replication of an experiment reported by Shin et al. [27] for finding the detection threshold for a moving screen in VR, and could mostly confirm prior results. With such a threshold, it is possible to unobtrusively move virtual screens to induce motion in the users and alleviate health risks due to prolonged sitting. In addition to replicating the prior VR study, we also extended the experiment to AR. There, we also found similar results, but the overall threshold for translations was about 39% lower than in our VR study, indicating that detecting small movements in AR could be easier. We speculate that perception differences between both VR studies and between VR and AR could be due to display resolution and visual details in the background. However, more studies are necessary to confirm this and determine the exact influence of these factors.

Acknowledgments

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