Eyes-Free Target Acquisition in Interaction Space around the Body for Virtual Reality

Yukang Yan[1], **Chun Yu**[123†], **Xiaojuan Ma**[4], **Shuai Huang**[1], **Hasan Iqbal**[1], **Yuanchun Shi**[123]
[1]Department of Computer Science and Technology
[2]Key Laboratory of Pervasive Computing, Ministry of Education
[3]Global Innovation eXchange Institute, Tsinghua University, Beijing, 100084, China
[4]Hong Kong University of Science and Technology, Hong Kong
yyk15@mails.tsinghua.edu.cn, {chunyu,shiyc}@tsinghua.edu.cn, mxj@cse.ust.hk

ABSTRACT

Eyes-free target acquisition is a basic and important human ability to interact with the surrounding physical world, relying on the sense of space and proprioception. In this research, we leverage this ability to improve interaction in virtual reality (VR), by allowing users to acquire a virtual object without looking at it. We expect this eyes-free approach can effectively reduce head movements and focus changes, so as to speed up the interaction and alleviate fatigue and VR sickness. We conduct three lab studies to progressively investigate the feasibility and usability of eyes-free target acquisition in VR. Results show that, compared with the eyes-engaged manner, the eyes-free approach is significantly faster, provides satisfying accuracy, and introduces less fatigue and sickness; Most participants (13/16) prefer this approach. We also measure the accuracy of motion control and evaluate subjective experience of users when acquiring targets at different locations around the body. Based on the results, we make suggestions on designing appropriate target layout and discuss several design issues for eyes-free target acquisition in VR.

ACM Classification Keywords

H.5.2. [Information Interfaces and Presentation]: User Interfaces: Input devices and strategies

Author Keywords

Virtual reality; target acquisition; eyes-free; proprioception.

INTRODUCTION

Virtual and augmented reality provides great potentials for various applications, such as gaming [10], education [23], medical training [14] and so on. In VR/AR, people directly acquire and manipulate virtual objects as if in the real world. Therefore, in VR/AR applications, object acquisition should be the fundamental operation. It would be of great significance to improve such a basic operation.

Figure 1. An illustrative scenario of eyes-free target acquisition in virtual reality. A user is doing design and he fetches tools in the interaction space around the body in an eyes-free manner. The FOV (field of view) size of his HMD is visualized (110 - 120 degrees).

Currently, acquiring an object in VR/AR is eyes-engaged: A user has to move or rotate his/her head to visually locate an object before acquiring it [21]. In physical world, however, acquisition of an object does not necessarily require eye's participation [12]. In many cases, by leveraging the spatial memory and proprioception, people can reach for an object in an eyes-free manner (e.g. a driver reaches gear stick while driving).

In this research, we want to take advantage of users' eyes-free input ability to improve interaction in VR/AR, by allowing users to acquire an object without looking at it. Figure 1 illustrates such an interaction. As shown, the user is wearing a VR HMD doing designs. He is facing his work in the virtual space. He might need to put color on it, observe it in detail, or to sculpture it during the design process. At these moments, he could just stretch out his hand to acquire different tools (e.g. pens, magnifying glass) at different positions around his body, without turning head to look at them. In this manner, the user's visual attention is always focused on the object he is editing. This makes the whole interaction process more fluent and immersive; meanwhile, it reduces head movements and could alleviate fatigue and VR sickness, which significantly affects user experience in VR [46].

---

†donates the corresponding author.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.

CHI 2018, April 21–26, 2018, Montreal, QC, Canada
© 2018 ACM. ISBN 978-1-4503-5620-6/18/04. . . $15.00
DOI: https://doi.org/10.1145/3173574.3173616

To the best of our knowledge, no research has investigated the ability of users to perform eyes-free acquisition in the interaction space around the body in VR/AR. To explore its feasibility and usability, we conducted three studies. In the first study, we explored user acceptance of eyes-free target acquisition. Users reported the comfort level they felt when acquiring the targets at different positions, and the minimum distance between targets that they needed to acquire them easily. In the second study, we tested the accuracy of the movement control when users acquired the targets. We measured the distance between users' acquisition points and the target's actual location. We also tested how body movement influenced the accuracy of users to acquire the target. In the third study, we compared the eyes-free approach with the eyes-engaged approach to explored the pros and cons and possible applications of eyes-free acquisitions. Based on the results of previous two studies, we located 18 targets at the positions which were both comfortable and accurate to acquire, and asked users to acquire them using two approaches. The results showed eyes-free acquisitions to be well-accepted and preferred (13/16), with higher acquisition speed, satisfying accuracy (92.59%), fewer distractions from ongoing tasks, less fatigue and less sickness. After three studies, we discuss the design implications and suggestions for the target layout eyes-free acquisition.

Our main contributions can be summarized as follows:

- This is the first work to explore the feasibility and usability of eyes-free target acquisition in virtual reality environment.
- We measured both accuracy and subjective acceptance of eyes-free target acquisition at different positions around the body.
- By comparing with the eyes-engaged manner, We showed the benefits of eyes-free target acquisition such as higher speed, less fatigue and VR sickness, and few distractions.

RELATED WORK

We first review previous work on target acquisition in 3D space and interactions around the body. We then discuss spatial memory and proprioception.

Target Acquisition in 3D space

There are two main approaches to acquire a target in 3D space: virtual pointing and virtual hand [2]. With virtual pointing (a.k.a. ray-casting pointing), a user emits a ray from his hand or the controller to point at the intended target [43]. Virtual pointing is suitable for selecting remote targets [7, 17, 38, 45]. With virtual hand, a user acquires a target directly by touching it with the controller or bare hand [33]. Virtual hand is usually used for interacting with objects around the body [42, 48]. Currently, most techniques of both virtual pointing and virtual hand require users to look at the target when acquiring it. Although previous work has studied the eyes-free use of virtual pointing [25], no research about the eyes-free use of virtual hand has been done.

Interactions around the Body

Researchers have proposed several techniques to interact in space around the body. The around-body space is easily accessible and can be used to expand the input vocabulary [3]. To enlarge the display space, Graspable [36] and Peephole displays [47] allow users to change the contents on the mobile device display by moving the device to different positions around the body. To shorten the process of triggering shortcuts on mobile devices, VirtualShelves [25, 26] enables users to launch different applications by orienting the mobile device to different directions. To expand the interaction space, *Chen* et al.[3] detect the spatial relationship between user and the mobile device and enable three types of around-body interaction.

To our knowledge, no research has studied the benefit of eyes-free target acquisition in around-body space in VR/AR. In VR/AR, users' spatial sense of objects is influenced due to the imperfect rendering of depth information [15, 24] and the limited FOV [46]. In this paper, we tested whether we can avoid these problems by acquiring targets in the eyes-free manner.

Spatial Memory and Proprioception

Human has the ability to acquire targets in the eyes-free manner [12]. This ability is mainly built on two factors: the spatial memory and the proprioception [6].

Spatial memory is the part of memory that is responsible for recording information about different locations and the spatial relations between objects [22]. It can help users efficiently retrieve positions of targets [5] in acquisition tasks. Previous work studied the ability and effectiveness of users to build the spatial memory, both in 2D [19] and 3D [5] spaces. A typical experiment of these studies works in such flow: users are first instructed to place [8] the targets or to memorize [22, 34] their positions; then they are tested to recall the positions. Based on the recall results, they could design the target layouts to help users easily build spatial memory. This process often takes a long time (four months in a previous study [8]) and many factors need to be controlled (landmarks [40, 41], mnemonic aids [4, 32]). In this paper, we mainly focus on the basic kinematic skills of acquiring positions after users have already built the spatial memory.

In addition, proprioceptive feedback is important for human's movement control [6]. Proprioception is the sense of position and orientation of one's body parts with respect to each other [26]. With the help of proprioception, users could perform eyes-free acquisitions of the targets on various platforms, such as on the back of a VR HMD (FaceTouch [18]), on a remote screen (Air Pointing [6]), or to select different directions by orienting a mobile device (VirtualShelves [25, 26]). Besides, users can leverage proprioception to control the body posture as an input modality (Pose-IO [28], FootGesture [35]). Most of these works studied the acquisition accuracy, which is presumably determined by the resolution of proprioception [37] and the acquisition speed, which is influenced by the reaction time of the proprioception [11]. Besides these two dimensions, users' sense of certainty about whether they can acquire the target correctly and the comfort level of the acquisition postures are also of great value to be studied. Because these subjective senses influence whether users adopt the approach. In this paper, our three studies progressively measured the subjective acceptance, control accuracy and acquisition speed of the target acquisition with only the proprioceptive feedback.

STUDY1: EXPLORING SUBJECTIVE ACCEPTANCE

Before testing the control accuracy and speed of eyes-free target acquisition, we decided to first look at the subjective acceptance of users for this interaction manner. As users acquire the target without looking at it, they might be not certain whether they have acquired the correct one. This sense of certainty could be alleviated by enlarging the distance between targets. When the targets are located more sparsely, the users should feel more confident to acquire one of them. Besides, if we locate targets at the positions that are difficult to reach, e.g. in very high regions, the arm postures of users to acquire them may cause fatigue and discomfort. Therefore, it is important to test the positions of the target that users feel comfortable to acquire and the minimum distance between the targets that they need to acquire them with certainty. The results also help us determine the appropriate target layout for testing the acquisition performance in the following studies.

Participants

We recruited 12 participants (4 females) from a local campus. They were between the ages of 22 and 26 (mean=24.2, SD=1.34). All the participants use their right hand as the dominant hand, with no physical injury or discomfort. 8/12 participants experienced VR applications before this study. 8/12 participants were familiar with mid-air gesture interaction. We measured the arm length (from shoulder to hand palm) of participants to be 67.95 cm (SD=3.22) on average.

Apparatus

We conducted the experiment on HTC Vive, and developed the software with Unity 5.60 engine in C#. Figure 2 shows the setting of the experiment and the task interface. Users held a controller on each hand and could select the required target with either of them according to the convenience. HTC Vive used a lighthouse positioning system [31] to track the head-mounted display and the two controllers. The tracking precision was reported to be less than 1mm [1].

Design

We designed two independent factors: the *position* of the target and the *posture* (stand vs. sit) of the user. We tested how these two factors affect the subjective acceptance of users when acquiring the target in the eyes-free manner. The subjective acceptance was measured on two aspects: the minimum distance between targets that users felt comfortable to interact with, and the comfort level of the arm while performing the acquisition. As shown in Figure 1, we sampled 60 positions on a circular sphere surface around the user's body. We determined the radius to be 65cm so that all positions could be acquired by users. We evenly segmented the horizontal angle range of -180 degrees to 180 degrees into twelve levels and the vertical angle range of -60 degrees to 60 degrees into five levels. We located the 60 positions at these horizontal and vertical angles.

Among the 60 positions, 9 were within the view, which were supposed to be acquired in the eyes-engaged manner. The other 51 positions, which were out of the view, were used to test users' subjective acceptance of the eyes-free acquisitions. Users were not allowed to turn head to look at the targets at these 51 positions. To ensure this, an experimenter watched the HMD display through a secondary screen during the experiment.

Figure 2. The setting of the experiment and the task interface in Study1. A user moved the controller to acquire the virtual sphere in the 5 × 5 grid. Then he turned head to see which sphere he had acquired (the red one).

For each of the 60 positions, we asked the user to determine the minimum distance between targets that made them feel certain when acquiring the target. To achieve this, we rendered a 5×5 grid of sphere targets (radius = 1.5cm), with the center target at the tested position. The initial layout of the targets was set to be dense, with a center-to-center distance between targets of 5 cm. We asked the user to acquire the center target eyes-freely, and then turned to see it to check whether it was acquired or not. Based on the result and their subjective feeling, they decided whether to increase the distance (one centimeter at a time) or stop. We recorded the distance where a user stopped to be the minimum distance that fulfilled the certainty requirement.

Task

Each user completed 2 sessions (*postures*) * 60 trials (*positions*) = 120 trials in the experiment. The order of the posture conditions was counter-balanced. The order of the target positions was randomized for each user. In each trial, the users determined the distance between targets through the process described above. After each trial, they rated the comfort level of the arm posture, in a five-point Likert scale.

Data Processing

We used RM-ANOVA to test the effects of the horizontal angle, vertical angle of the positions and the posture (sit vs. stand) on the minimum distance between targets. We used Friedman test to test their effects on the comfort levels.

Results

Figure 3 summarizes the result on different horizontal and vertical angle levels. The centers of the circles were at the 60 positions we tested. The radiuses were the minimum distances between targets at each position, averaging the results of twelve participants and two postures. The colors were mapped to the comfort levels at each position. Overall, we found that for different positions, the subjective acceptance of eyes-free acquisitions of users was different.

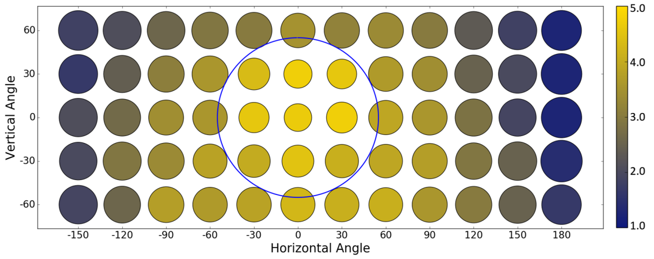

Figure 3. The circles summarize the comfort level (color) and the minimum distance between targets (radius) for different target positions (centers) when users acquired them.

Effects of Position

The results showed that the height of the targets significantly affected the minimum distance between targets ($F_{4,44} = 5.173$, $p = 0.002$) and the comfort level ($X^2(4) = 18.02$, $p = 0.001$). Post-hoc tests showed when targets were located at 60 degrees vertically (the highest level), the minimum distances between targets (mean = 10.87cm) were significantly larger than those at 0 and 30 degrees (mean = 9.97cm, 10.08cm; $p = 0.001$, 0.008), and the averaged distance was also larger than those at -30 and -60 degrees (mean= 10.35cm, 10.35cm). For the comfort level, when the targets were located at 30 and 60 degrees, the ratings (mean = 3.15, 2.65) were lower than those at lower heights (mean = 3.26, 3.32, 3.30). Users reported that when position of the target was high, they need to raise their arms with large amplitudes to acquire it, which caused fatigue. Meanwhile, the control of the hand over head was more unstable, compared to that at lower heights. So, they needed larger distance between the targets to make sure they could acquire the correct one. "*It is very tiring to acquire the targets above my head.*" [P3] "*When I lifted my arm, the jitters limited my accuracy.*" [P1]

Also, we found the horizontal angle of the target position significantly affected the minimum distance between targets and the comfort level ($F_{11,121} = 31.451$, $p < 0.001$; $X^2(15) = 117.58$, $p < 0.001$). Specifically, we found when the angle changed from 0 degrees to both sides (180 and -180 degrees), the distance became larger and the comfort level became lower, as shown in Figure 4. Users reported that when the positions were in the rear, they need to rotate their arms to the uncomfortable directions to acquire them. This would cause fatigue even some pain, which reduced the comfort level. Also, the control accuracy dropped because of the uncomfortable arm postures. "*The positions in the rear were very difficult to reach and the postures were uncomfortable.*" [P5] Besides, users also reported that they felt it easy to acquire the positions at 90 degrees and -90 degrees horizontally, as they could reach the positions by only raising the arm without any rotations.

Effects of posture, visibility and hand side

The results showed that the minimum distance between targets and the comfort levels for stand and sit conditions have no significant difference ($F_{1,11} = 1.710$, $p = 0.218$; $X_2(1) = 0.37$, $p = 0.544$). Although the overall results showed little difference, the participants reported that their control of arms and hands was more flexible in the stand condition, but more stable in the sit condition.

There were nine positions of the targets that were within the field of view (blue circle in Figure 3) and participants could see the targets when acquiring them. We compared the data of these positions to the data of the other positions out of the view. Student's test showed that when the target was located out of the view, users needed significantly larger distances between targets to acquire it ($t = 9.44$, $p < 0.001$). The larger distances that users needed reflected the more uncertainty that they felt when acquiring the positions out of the view in the eyes-free manner. The average distance of the positions within the view was 7.63cm (SD = 2.88cm), which was still larger than the distance at the beginning (5cm). Users reported that they felt uncomfortable to perform very careful controls in a dense layout, even if they could see the target. The comfort level of positions within the view was tested to be significantly higher than that of the positions out of the view by Student's test ($t = 9.44$, $p < 0.001$). The positions within the view were all in the front region, where users frequently interacted in daily life. Users were used to the arm postures to acquire these positions and therefore felt them to be more comfortable.

As Figure 4 shows, the minimum distance between targets and comfort levels distributed symmetrically on both sides. As users acquired the targets with different hands on two sides, we tested whether different hands would affect the values of these two metrics. The RM-ANOVA results showed that different hands made no significant difference ($F_{1,11} = 1.73$, $p = 0.19$) on the minimum distance between targets. On the other hand, the results of the Friedman test showed that the positions acquired by the right hand resulted in significantly higher comfort levels ($X^2(1) = 6.03$, $p = 0.014$). This is possibly because all of the participants were right-handed and they were more accustomed to acquiring objects with the right hand.

Correlation between comfort and accuracy

As shown in Figure 4, we found a negative correlation between the distance and the rating, supported by a Point-Biserial test (correlation = -0.99, $p < 0.001$). We also tested this correlation for all 60 positions and two postures. The results showed significant correlation between the two metrics (correlation = -0.31, $p < 0.001$). This result was consistent with the user feedback that for the positions which caused more fatigue or discomfort, the arm postures to acquire them were also difficult to control.

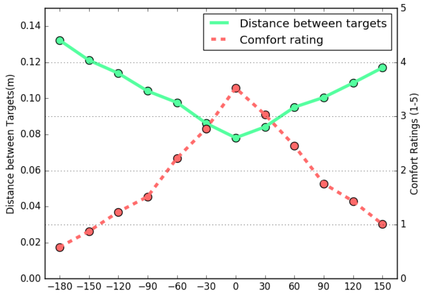

Figure 4. The averaged distances between targets and comfort ratings of the target positions with different horizontal angles.

STUDY2: ACCURACY OF CONTROL

The goal of this study was to test the accuracy of movement control when users acquire targets in the eyes-free manner. To achieve this, we asked users to acquire a target which was located at different positions around the body. We analyzed the acquisition points compared to the target's actual locations. In addition, users might turn to different directions while interacting in real applications. For example, if an architect is working in the middle of different tables around him in VR, he might need to change his body orientation for manipulating objects on those tables. So we investigated how the accuracy of target acquisition would be affected after the users rotated their bodies. Based on the accuracy results and the subjective acceptance results obtained in Study 1, we make suggestions on interaction design of eyes-free target acquisitions.

Participants

We recruited 24 participants (4 females) from the local campus, aged from 20 to 26 (mean=23.21, SD=1.64). Six of them had taken part in Study 1. All of the participants used their right hand as the dominant hand. Ten of them experienced VR applications before the experiment. They rated for VR sickness (5-point Likert scale) before the experiment, and their average score was 2.2 (SD=1.02).

Apparatus

We used the same apparatus as in Study 1. In this experiment, we rendered a virtual office with furniture (e.g. whiteboard, shelves) in it to help users build a spatial sense of the environment. The target was rendered as a green sphere. Users pressed the trigger on the controller to acquire the target.

Design

We designed two independent factors: 1) the *position* of the target relative to the user and 2) the number of *rotations* that the user performed before acquiring the target. We tested how those factors affected the accuracy of the user when he/she was acquiring the target. We located the target at the same 60 different positions (5 vertical angles × 12 horizontal angles) around the user's body as tested in Study 1. For each target position, the users had to acquire the same target for twelve times by rotating their bodies into twelve different directions (the 12 horizontal angles). During the twelve acquisitions, the absolute position of the target did not change while the relative position of the acquisition changed when the user rotated his/her body. For instance, as shown in Figure 5, the user rotated from the *left* to the *right*, and the relative horizontal angle of the target to the user changed from *alpha* to *phi*. A target acquisition was registered when the user pressed the trigger on the controller to confirm it.

We defined two types of metrics to measure the accuracy of the target acquisitions: *spatial offset* and *angular offset*. *Spatial offset* was defined as the Euclidean distance [9] between the acquisition point and the target's actual position. *Spatial offset* should be small if users accurately acquired the target. We also calculated the *angular offset* of the acquisitions to analyze to which directions the acquisition points were shifted from the target's actual location. We translated the acquisitions points and the target positions from Cartesian coordinates (x, y, z) to spherical coordinates (horizontal degrees, vertical degrees). *Angular offset* was defined as their differences on the horizontal and vertical axis in degrees. Besides, we recorded the amplitude that users moved their head to acquire the target.

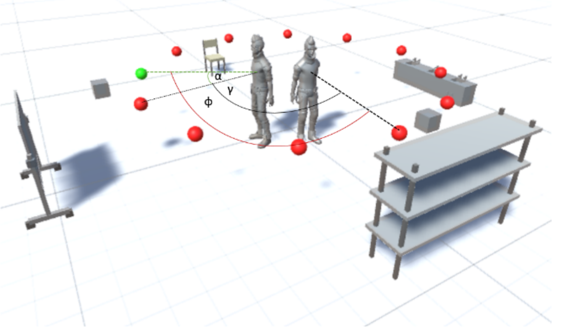

Figure 5. The concept of the experiment settings. The furniture indicates the virtual surroundings of the participants. The red spheres indicate the twelve directions that the participants rotate to, and the green sphere indicates the positioned target.

Task and Procedure

Before the experiment, the users were given time to familiarize themselves in the virtual room and its surroundings. This step was to let them develop a spatial sense of the environment. They looked around the room and touched the furniture with the controllers to understand the locations. The process took around ten minutes until users reported that they were very familiar with the space.

Each user performed 720 trials of target acquisition (60 sessions × 12 trials). At the beginning of each session, the user turned to the starting direction. Then we informed him/her the position where a target sphere was located, by its spherical coordinate, e.g. "30 degrees horizontally, 60 degrees vertically". We informed the coordinates to help users find the target faster; otherwise, she needed to visually search the target. After the user found the target, she observed the position, and moved the controller to touch it. She performed this procedure several times until she thought she had already remembered the position of the target. The user was required to remember this position in the following twelve acquisitions, which was reported to be easy. In each trial of acquisition, the user faced towards one specified direction and acquired the target without turning head to look at it. To help calibrate his/her orientation, we rendered a cube in that direction. After the acquisition, we told the user which direction to go next - e.g. "60 degrees right". The user turned to that direction and then he/she acquired the target again. To avoid the situation of users seeing the target during rotation, which might bias the accuracy result, we set the target to be invisible once the session began. After completing twelve trials, the target was located to a new position and a new session began. Both the order of the target positions and the directions after rotation were randomized for each participant. The whole experiment took around an hour on average, with a break given every twenty sessions.

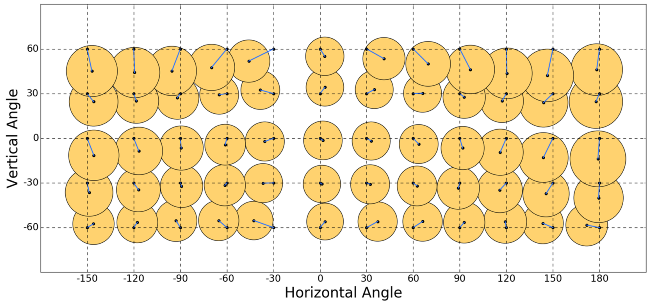

Figure 6. Summary of the main results of this experiment. The centers of the circles are the averaged positions of twelve acquisitions of 24 users and radiuses are the standard deviations. The blue lines visualize the offsets of the average positions from the target's actual positions. All coordinates and lengths are converted to angles in degrees.

Data Processing

We totally collected data of 24 (participants) × 720 (trails) = 17280 acquisitions. In the data processing, we removed 1.12% of the acquisitions because their *spatial offsets* and *angular offsets* were both out of the range of three times deviation from the averaged values. We performed RM-ANOVA to analyze the effects of the positions (horizontal and vertical angles) of the target and the number of rotations users performed before acquiring the target (0 to 11) on the *spatial offset*, *angular offset* and the head movement amplitudes.

Results

Figure 6 visualized the main results of this experiment. The circles summarize the acquisition points of different target positions, which show that the accuracy of the acquisitions (offsets) and the closeness of the acquisition points (standard deviations) were different for different target positions.

Spatial Offset

Overall, we found that in the eyes-free manner, the acquisition points had large spatial offsets from the target's actual positions. The averaged spatial offsets for different target positions ranged from 1.9 cm to 19.1 cm, with the standard deviations to be 12.5 cm to 29.0 cm.

RM-ANOVA results showed that horizontal angles of the target positions significantly affected the spatial distance of the acquisitions ($F_{11,253} = 95.48$, $p < 0.001$). The green line in Figure 7(c) visualizes the difference of the averaged offsets for twelve horizontal angles of the target positions. As shown, the values increased from 0 degrees in the front to both sides (-180 degrees and 180 degrees), which roughly reflected the reduction of users' control accuracy. The horizontal angle of the target position determined the horizontal abduction or adduction degrees of the users' arms when they acquiring the target. While the abduction angle of the human arm has a limitation of around 40 degrees [13]. When the target was located at the positions out of this range, users need to both rotate their bodies and their arms to acquire it, which might influence the accuracy of movement control. As users reported, the effects were extremely significant when the targets were in the back, "*For the target in the back (-180 degrees, 0 degrees), my shoulder obstructed my arm from reaching it and I could not move the controller precisely.*" [P2]

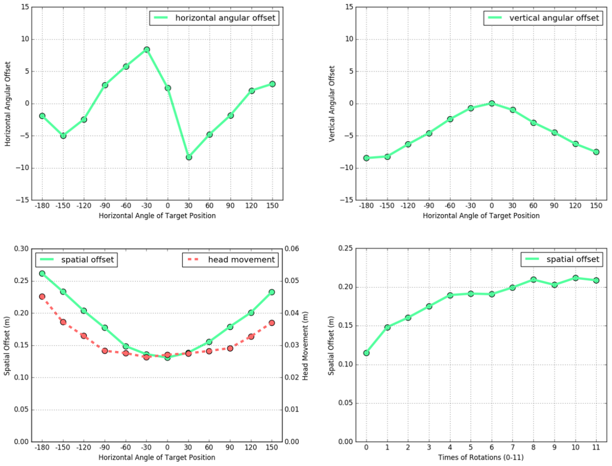

Figure 7. (a) The horizontal angular offset of the acquisitions at different horizontal angles; (b) The vertical angular offset of the acquisitions at different horizontal angles; (c) The spatial offset and head movement amplitudes of the acquisitions at different horizontal angles; (d) The spatial offset of the acquisitions after different times of rotations.

Vertical angle was also tested to significantly affect the spatial offset of the acquisitions ($F_{4,92} = 22.76$, $p < 0.001$). The average values are shown in Table 1. Post hoc tests showed that spatial offsets of 0 and 60 degrees had no significant difference (p = 0.838), but the difference between the spatial offsets of each pair of 0, 30, -30 and -60 degrees was significant (all $p < 0.05$). Higher positions require users to lift their arms with larger amplitudes to acquire, and the resulted fatigue and jitters reduced their accuracy of movement control. This explains why spatial offsets increased as the target position became higher, except for 0 degrees. For 0 degrees, users raised their arm horizontally, which produced the largest torque, might also cause heavier fatigue and therefore reduced the accuracy.

RM-ANOVA also showed a significant effect of the number of rotations on the spatial offset ($F_{11,253}=70.46$, $p<0.001$). As Figure 7(d) shows, the spatial offset of the acquisition increased with the number of rotations users performed before the acquisition. Users' body orientation changed after each rotation, and they need to reintegrate the proprioceptive information before acquiring the target again. The result indicates that their ability to reintegrate proprioception decreased with the number of rotations. Post hoc tests showed that the spatial offset of the first of the twelve acquisitions was significantly smaller than the others (all $p < 0.001$). This showed that their reintegration ability dropped most significantly after the first rotation.

	Vertical Angle Levels				
	-60^o	*-30^o*	*0^o*	*30^o*	*60^o*
Mean (cm)	15.0	17.2	20.8	19.3	21.0
Std (cm)	1.0	0.7	1.0	0.9	1.1

Table 1. The mean value and standard deviation of the spatial offset for acquisitions at different vertical angles.

Angular Offset

RM-ANOVA results showed that the horizontal angle of the target position significantly affected the horizontal angular offset of the acquisitions ($F_{11,253}$ = 16.367, $p < 0.001$). As shown in Figure 7(a), along the horizontal angle of the target position, the horizontal angular offset distributed symmetrically about the point of 0 degrees. The absolute value of 0, 90, 180, -90 degrees was small (mean < 4 degrees). This showed that users had better sense of these directions, and they had higher precision of arm control on two sides (90 and -90 degrees), also possibly because they only need to raise the arm without horizontal rotations of the shoulder. For the other horizontal angles, the shoulder obstructed the arm rotation in different levels and produced angular offsets shifted away from the body.

RM-ANOVA results showed the horizontal angle of the target position significantly affected the vertical angular offset of the acquisitions ($F_{11,253}$ = 178.428, $p < 0.001$). As Figure 7(b) shows, the vertical offset increased symmetrically as the horizontal angle changed from 0 degrees to both sides (180 and -180 degrees). Users created very small vertical offsets (mean < 1 degree) when acquiring targets at 0 degrees horizontally in the front. They reached the positions lower than the target's actual position when the target was located on both sides, and the offset value became maximum when it was at 180 degrees in the back (around 8 degrees). We observed that as the horizontal angle (absolute value) of the target position increased, users need to abduct the shoulder at a larger angle to acquire it. This resulted in a smaller vertical range that they could raise their arm and therefore reached a lower position. Results also showed the vertical angle of the target position also significantly affected the vertical offset ($F_{4,92}$=113.814, $p<0.001$). Except for -60 degrees (mean = 3.52 degrees), users created negative vertical offsets (mean = -8.45, -1.70, -6.74, -3.72) for other vertical angles.

Head Movement Amplitudes

We used the head movement data to partially reflect the amplitude users rotated their body. RM-ANOVA results showed that the horizontal angle of the target position had significant effects ($F_{11,253}$ = 47.012, $p < 0.001$) on the amplitude of users' head movement. As Figure 7(c) shows, similar to the spatial offset, the movement amplitude increased as the target positions changed from 0 degrees in the front to both sides. The feedback from users was consistent with the result: when the target was in the front (-90 to 90 degrees horizontally) they did not need to rotate their body, but they rotated in larger amplitude as the target moved to the rear region.

Discussion

Based on the results of Study1 and Study2, our suggestions for the future UI design of eyes-free target acquisitions in this space shows the following:

Several dimensions need to be considered when choosing the locations of components of the UI: the sense of comfort and certainty, the control accuracy and stability, and the physical effort of users when they acquired the location. Overall, we found the horizontal ranges over 150 and -150 degrees (the rear region) resulted in poor performance in these dimensions and not very appropriate to locate targets. While for vertical angles, the region at or near -60 degrees below was perceived easy to access and also had satisfying control accuracy, which can be used to arrange targets.

For the acquisition judgment, we suggest using the techniques like "area cursor" [44] or "bubble cursor" [16] to improve the accuracy, as the average spatial offset of the acquisition positions to the target's actual location was tested to be 18.6 cm. Designers could decide the size of the bubble or the area parameter by referring our results. We also found the averaged positions of users' acquisition points had offsets of 1.9 to 19.1 cm when target was located at different positions. We suggest using the positions added by the offsets to judge which objects users intend to acquire. In our experiment, although we did not require participants to distinguish different target positions, the accuracy of distinguishing 60 positions was simulated to be 74.99%. If we add the offsets to the target positions, the accuracy was improved to 78.17%.

In this study, we tested the accuracy of target acquisition on 60 positions, which were evenly sampled on a sphere surface. Based on these results, we can also interpolate the accuracy performance (offset and deviation) of users when acquiring targets at other positions on this surface. As the standard deviation reflected the closeness of the acquisition points, we can statistically predict the accuracy rate of target acquisitions in different target layouts. Figure 8 shows the interpolation result of the standard deviations, which designers could refer to arrange target locations for eyes-free target acquisitions.

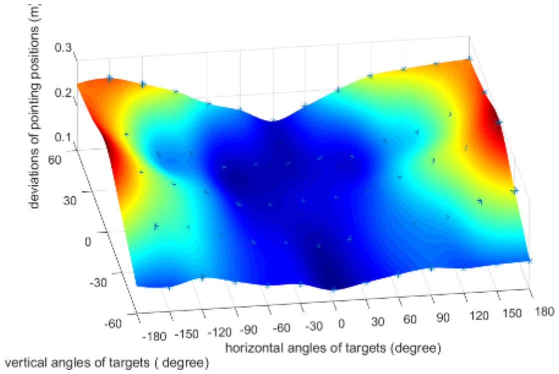

Figure 8. The interpolation of the standard deviations of the target acquisition points on the whole surface, visualized into a heat map.

STUDY 3: COMPARE EYES-ENGAGED AND EYES-FREE TARGET ACQUISITION

In this study, we aimed to examine the performance of eyes-free target acquisition, and compare it to the eyes-engaged approach. We examined the advantages and shortcomings of eyes-free acquisition on acquisition performance (speed, accuracy), user experience (fatigue, sickness, distraction) with the acquisition task among 18 targets in VR. The performance of two approaches was compared in different conditions of different FOV (field of view) sizes and whether users need to simultaneously perform another second task which required them to visually focus on. We also wanted to obtain users' subjective feedback and preference over the two approaches.

Hypothesis

There are three hypotheses we aim to test in this study:

H1: The eyes-free condition should result in higher acquisition speed, less distraction to ongoing tasks, less fatigue, and less sickness because it requires fewer head movements and focus changes.

H2: The eyes-free condition should have a satisfying acquisition accuracy after we optimized the acquisition judgment by using an "area cursor" mechanism and including the statistically predicted offsets into the judgment, which was suggested by Study 2.

H3: Based on H1 and H2, users should prefer the eyes-free approach than the eye-engaged approach, especially when the FOV is small or there is another ongoing task.

Participants

16 participants (4 females) were recruited at the local campus to take part in this study. They were between the ages of 20 and 26 (mean=23.0, SD=1.45). All the participants use their right hand as the dominant hand. Twelve of them had experienced VR devices before this study. Three of the participants reported they feel slight sickness when watching 3D movies and VR videos.

Apparatus

We used the same apparatus as in Study 1 and Study 2. We rendered an empty room as the environment. As Figure 9 shows, the targets were rendered as two 3×3 grids of spheres out of view, with one on each side of the user's body. Users moved the controller and pressed the trigger to acquire the targets. In the front, we rendered a shortcut of the target layout to show which target users should acquire. When users performed the second task, we also rendered the characters they should recognize. After each acquisition, a sound was played to inform users whether they acquired the correct target.

Design

We used a within-subject design. The independent factors were *Approach* (eyes-free/eyes-engaged), *FOV* (30/110 degrees) and *Second Task* (performed/not performed).

For *Approach*, *eyes-free* condition required participants to face the front and acquire the targets on both sides without turning head to look at them; *eyes-engaged* condition required participants to search for the targets and acquire them when they saw them in the view. For *FOV* size, we used 110 and 30 degrees, two typical sizes of VR (Vive) and AR (HoloLens) devices. We rendered the FOV size of 30 degrees on Vive to keep the experiment condition consistent, by making the content outside of 30 degrees to be dark.

To measure the distraction that the target acquisition actions cause from users' ongoing tasks, we designed a *second task* to ask them to perform simultaneously. This task required users to observe the characters ('a', 'b', 'c') appearing in the front and report to the experimenter when the character turned to be 'a' by saying it. We counted the number when they missed saying 'a' as the metric of the distraction caused by target acquisitions. We also counted the false positives, to avoid the situation of users saying 'a' without recognition, which hardly appeared (< 20 times for all users) in the experiment. We referred the design of this second task from the previous studies [27].

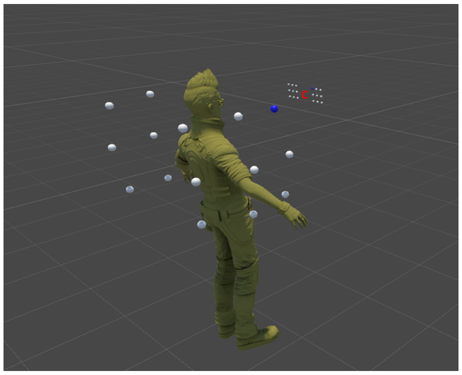

Figure 9. The concept of the experiment setting. Targets were located on both sides of users' body. A shortcut of the target layout was visualized in the front, as well as the character for the second task.

We located 18 sphere targets at the positions that users could both comfortably and accurately acquire, which was tested in Study 1 and Study 2. As Figure 9 shows, the spheres were arranged as two three by three grids on both sides of users, which had equal distance (65cm) to users' chest. Two center spheres were located at the coordinates of (-90 degrees, 0 degrees) and (90 degrees, 0 degrees). The distances between adjacent targets were equal (31.5cm). We did not require users to memorize the positions of different spheres. However, as previous research tested, users could memorize 14 to 20 3D positions of targets after a short training [4, 29, 39]. So we thought it appropriate to test 18 targets in this study. We informed both which sphere to acquire as well as its position by a shortcut of the target layout in the front, shown in Figure 9. Users confirmed they could easily understand the position of the target sphere with its help.

We measured the speed of each acquisition of the target by the time between each target appeared (2 seconds after last acquisition) to the time the users pressed the trigger to acquire it. We measured the accuracy as the rate that the acquired sphere was the target sphere. To judge which sphere users were acquiring, we calculated the nearest distance between the positions of the spheres and the actual position where users located the controller and pressed the trigger. For eyes-free condition, we calculated the sphere positions by adding the spatial offsets we measured in Study 2.

Task

Each user performed 8 sessions (2 *Approach* × 2 *FOV* × 2 *Second Task*) × 8 trials × 18 acquisitions = 1152 acquisitions. The order of eight different conditions was counter balanced. The first two trials of each session were the warm ups to help users familiarize themselves with the sphere layout and the conditions. Each session took around ten minutes to complete, after which we collected subjective feedback about user experience in a questionnaire - the NASA task-load [20] and sickness ratings. Moreover, we interviewed users for their

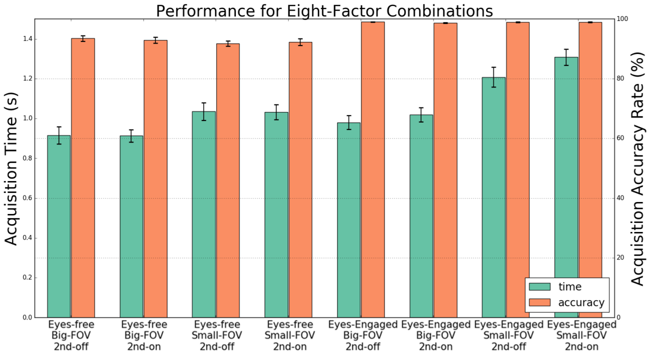

Figure 10. The speed (average acquisition time) and accuracy (rate) results of the acquisitions in different conditions. The error bars represent the standard deviations.

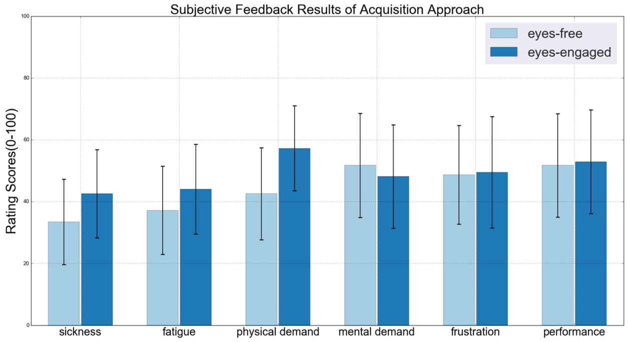

Figure 11. User's subjective ratings for the experience using two approaches to acquire targets. The error bars represent the standard deviations.

comments on both acquisition approaches and their preference after the whole experiment. The experiment took around 90 minutes to complete, with a break given every two sessions.

Results

We finally collected 16 participants × 8 sessions × 6 trials × 18 acquisitions = 13824 acquisitions of targets. We performed full factor RM-ANOVA to test the effects on user performance and a Wilcoxon test to compare the subjective ratings of two approaches.

Speed

The results supported H1 that eyes-free acquisitions (mean=0.974s) were significantly faster than eyes-engaged acquisitions (mean = 1.132s; $F_{1,15} = 28.335$, $p < 0.001$). Also, the acquisition speed was significantly lower ($F_{1,15} = 35.815$, $p < 0.001$) when the FOV size was smaller. An significant interaction between approach and FOV ($F_{1,15} = 35.815$, $p < 0.001$) showed that the speed dropped significantly more sharply for the eye-engaged approach (delta = 0.231s on average) than the eyes-free approach (delta = 0.086s on average) when the FOV was smaller. Eyes-free approach gained a speed advantage because it did not require users to turn heads or search the targets in the view, which was time-consuming. When the FOV was smaller, the head rotation and the search cost more time using eyes-engaged approach, because users need to rotated head with larger amplitudes and perceived a poorer sense of space in smaller FOV [46]. As this hardly affected the eyes-free approach, the speed difference of two approaches was magnified. Besides, results showed no significant difference of acquisition speed made by whether there was a second task ($F_{1,15} = 1.819$, $p = 0.197$; mean = 1.035s, 1.071s).

Accuracy

The results supported H2 that the eyes-free approach had a satisfying acquisition accuracy (mean = 92.59% for 18 targets). However, compared to eyes-engaged approach (mean = 98.87%), users still made significantly more errors ($F_{1,15} = 64.475$, $p < 0.001$). Without visual feedback, the control accuracy of users had a significant reduction. However, relying on the proprioception, users could still acquire a sufficient number (18) of targets for most interaction tasks[30] in the space around the body. We also evaluated the benefits of adding the offset results obtained in Study 2 into the target judgment of acquisitions. We simulated to use the original positions of the spheres to judge which spheres users acquired, and the accuracy rate dropped to 91.14%. Besides, we found no significant difference that FOV or second task made on the accuracy rate ($F_{1,15} = 0.897$, $p = 0.359$; $F_{1,15} = 0.377$, $p = 0.548$).

Second Task Performance

The results of the second task performance supported H1 that the eyes-free approach caused less distraction from the ongoing task. RM-ANOVA showed that eyes-engaged approach (mean response = 89.911%) caused significantly more misses of the second task than the eyes-free approach (mean response = 97.176%; $F_{1,15} = 40.196$, $p < 0.001$). As the eyes-free approach avoided users from frequent focus switches, they could pay continuous visual attention to the second task. Also, users' response rate of the second task was significantly lower when the FOV size was smaller (mean = 91.70%, 95.39%; $F_{1,15} = 7.073$, $p = 0.018$). A significant effect of approach and FOV ($F_{1,15} = 4.843$, $p = 0.044$) showed the difference of two approaches was magnified when the FOV size was smaller. The eyes-free approach gained larger advantage (delta increased from 4.64% to 9.90%), possibly because users took longer time to acquire the target using the eyes-engaged approach, and therefore missed even more contents of the second task.

Subjective Feedback

The results of Wilcoxon test supported H1 that users perceived less fatigue ($Z = -4.528$, $p < 0.001$) and less sickness ($Z = -5.305$, $p < 0.001$) using the eyes-free approach compared to the eyes-engaged approach. As the eyes-free approach reduced head movements of users, it effectively alleviated users' physical demand ($Z = -6.226$, $p < 0.001$) and their VR sickness. However, using the eyes-engaged approach allowed users to roughly turn heads to the region where the target was located and visually search it after the head rotation. While the eyes-free approach required users to think clearly about the exact position of the target before acquiring it. As a result, there was a tendency that users perceived heavier mental demand using the eyes-free approach. Besides, results showed no significant difference of two approaches on frustration or perceived performance. Figure 11 visualizes the subjective ratings in all dimensions.

Additionally, we collected participants' comments about their preference between two approaches. 13/16 participants expressed their overall preference of eyes-free acquisitions. We interviewed the participants who preferred the eyes-engaged approach. They reported that they got more confidence if they see the target when acquiring it and one participant felt lazy to think of the exact positions. "*In my opinion, to think of the target's position was harder for me than to search it*" [P8]. For the participants who preferred the eyes-free approach, they reported that they saved time and effort from head rotations and the visual search using eyes-free approach; when there was a second task, the eyes-free acquisition helped them avoid missing contents they intended to observe. "*When I searched for the target visually, I didn't know whether I missed a task or not.*" [P4]; when the FOV was small, the eyes-free acquisition helped them avoid the heavy cost of turning heads. "*I didn't want to turn my head in the smaller FOV at all, because to turn my head in larger scale made me feel sick.*" [P5] One participant also proposed a hybrid method of the two conditions, "*I would like to search for the nearby targets and for the targets behind me, I hope to grasp them eyes-free*" [P10]. The overall comments supported H3.

DISCUSSION

Target Layout for Eyes-free Acquisition

Based on the results of Study 1 and Study 2, we suggest not to place targets at very high heights or in the right back region. The targets in our studies were rendered as spheres. However, participants also gave suggestions on the layout design of real objects. They suggested that the arrangement of the positions of the objects should be consistent with their daily experience. For example, they prefer to place the light switch in the high region and the trash bin at feet. As the region in the back is difficult to reach, they prefer to place the seldom-used objects there. For the objects that they use in pair (pen and paper), they suggest them to be placed on both sides and then they could acquire them with both hands. The target layout in Study 3 was pre-defined, however, in the future, we can test how the performance and user experience will be affected if users define the target layout themselves.

Design Implications for Real Applications

To utilize eyes-free acquisition in real applications, there are still some design details to be discussed. First, the false positives need to be avoided. In Study3, we calculated the nearest target to the user's acquisition point to be the selected one. This implementation may meet some false positive problems. We could use an area cursor with a smaller threshold (10-20 cm) to reduce this risk, but if so, we need to undertake the loss of accuracy as the trade-off. In Study3, we designed a second task to test the situation that there was an ongoing task when users need to acquire an object. The intensity of the task in our experiment was fairly low. Users only need to distinguish three types of characters ('a', 'b', 'c'). When the intensity of the ongoing task increase in the real applications, e.g. in a shooting game, the user performance might be more affected. For the AR applications, designers could refer to our results of 30 degrees FOV size condition in Study 3, but need to take other factors into consideration. We set the content out of the view to be pure dark, while AR applications actually allow users to see the real surroundings. Users possibly could leverage the real objects as landmarks, which could help them locate targets and build spatial memory [41], and may result in higher acquisition performance. Besides the designer example we discussed, the eyes-free acquisition approach may benefit other applications that involve frequent tool manipulations and switches, e.g. fighting games with weapons. As shown in Study3, users could focus on the ongoing work, enemy or other contents and acquire objects with less distraction.

LIMITATION AND FUTURE WORK

In this paper, we leave some factors of the eyes-free acquisition approach to be studied in the future. One factor is the feedback of the acquisition. Besides users' own proprioceptive feedback, providing tactile or auditory feedback will probably help users make sure they touch the targets. In the future, it is valuable to investigate the feedback design, including the type, the pattern and strength design. Another factor is the distance between the target and the user. All the target positions tested in this study had equal distance to the user's body, which could be easily accessible. We could further study the user performance and experience when the target is located nearer or further. A third factor is the reference frame. As Cockburn summarized, the spatial locations could be absolute, relative to external objects, the body, the device or some hybrid combination [6]. In our experiments, we placed the targets to absolute positions, because it is consistent with the experience of the real world and we also keep the layout stable which supports users' proprioception [19]. We will explore the possibility that users could eyes-free acquire targets in a body-referenced or controller-referenced frame in the future.

CONCLUSION

In this paper, we studied eyes-free acquisition of targets in the interaction space around body for VR through three studies. In Study 1 and Study 2, we tested the subjective acceptance and control accuracy of the eyes-free acquisition. We explored the positions that users felt comfortable to acquire and the minimum distance between targets that they needed to acquire them with certainty. Then we measured the offset from users' acquisition point to the target when it was located at different positions and tested the influence of body rotations made on their control accuracy. In Study 3, by comparing the eyes-free approach to the eyes-engaged approach, we showed that eyes-free target acquisition provided the benefits of faster speed, less fatigue and sickness, and less distraction from other ongoing tasks. While it might cause heavier mental demand and relatively lower accuracy (92.59% vs. 98.87% for 18 targets) as the trade-off. Overall, most users (13/16) preferred eyes-free acquisition over eyes-engaged acquisition, especially when the FOV was small or there was a second task. Based on the results and user feedback, we make suggestions on layout design and design implications for real applications.

ACKNOWLEDGEMENT

This work is supported by the National Key Research and Development Plan under Grant No. 2016YFB1001200, the Natural Science Foundation of China under Grant No. 61672314 and No. 61572276, Tsinghua University Research Funding No. 20151080408, and also by Beijing Key Lab of Networked Multimedia.

REFERENCES

1. 2017. HTC Vive. Website. (2017). Retrieved August 28, 2017 from `https://www.vive.com/us/`.
2. Ferran Argelaguet and Carlos Andujar. 2013. A survey of 3D object selection techniques for virtual environments. *Computers & Graphics* 37, 3 (2013), 121–136.
3. Xiang 'Anthony' Chen, Julia Schwarz, Chris Harrison, Jennifer Mankoff, and Scott Hudson. 2014. Around-body Interaction: Sensing and Interaction Techniques for Proprioception-enhanced Input with Mobile Devices. In *Proceedings of the 16th International Conference on Human-computer Interaction with Mobile Devices & Services (MobileHCI '14)*. ACM, New York, NY, USA, 287–290. DOI: `http://dx.doi.org/10.1145/2628363.2628402`
4. Andy Cockburn. 2004. Revisiting 2D vs 3D Implications on Spatial Memory. In *Proceedings of the Fifth Conference on Australasian User Interface - Volume 28 (AUIC '04)*. Australian Computer Society, Inc., Darlinghurst, Australia, Australia, 25–31. `http://dl.acm.org/citation.cfm?id=976310.976314`
5. Andy Cockburn and Bruce McKenzie. 2002. Evaluating the Effectiveness of Spatial Memory in 2D and 3D Physical and Virtual Environments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '02)*. ACM, New York, NY, USA, 203–210. DOI:`http://dx.doi.org/10.1145/503376.503413`
6. Andy Cockburn, Philip Quinn, Carl Gutwin, Gonzalo Ramos, and Julian Looser. 2011. Air pointing: Design and evaluation of spatial target acquisition with and without visual feedback. *International Journal of Human-Computer Studies* 69, 6 (2011), 401–414.
7. Nathan Cournia, John D. Smith, and Andrew T. Duchowski. 2003. Gaze- vs. Hand-based Pointing in Virtual Environments. In *CHI '03 Extended Abstracts on Human Factors in Computing Systems (CHI EA '03)*. ACM, New York, NY, USA, 772–773. DOI: `http://dx.doi.org/10.1145/765891.765982`
8. Mary Czerwinski, Maarten Van Dantzich, George G Robertson, and Hunter G Hoffman. 1999. The Contribution of Thumbnail Image, Mouse-over Text and Spatial Location Memory to Web Page Retrieval in 3D.. In *INTERACT*. 163–170.
9. Per-Erik Danielsson. 1980. Euclidean distance mapping. *Computer Graphics and image processing* 14, 3 (1980), 227–248.
10. Geoffrey M Davis. 1995. Virtual reality game method and apparatus. (June 13 1995). US Patent 5,423,554.
11. Michel Desmurget and Scott Grafton. 2000. Forward modeling allows feedback control for fast reaching movements. *Trends in cognitive sciences* 4, 11 (2000), 423–431.
12. Darren Edge and Alan F. Blackwell. 2009. Peripheral Tangible Interaction by Analytic Design. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction (TEI '09)*. ACM, New York, NY, USA, 69–76. DOI: `http://dx.doi.org/10.1145/1517664.1517687`
13. Michael Feltner and Jesus Dapena. 1986. Dynamics of the shoulder and elbow joints of the throwing arm during a baseball pitch. *International Journal of Sport Biomechanics* 2, 4 (1986), 235–259.
14. Anthony G Gallagher, E Matt Ritter, Howard Champion, Gerald Higgins, Marvin P Fried, Gerald Moses, C Daniel Smith, and Richard M Satava. 2005. Virtual reality simulation for the operating room: proficiency-based training as a paradigm shift in surgical skills training. *Annals of surgery* 241, 2 (2005), 364.
15. Leo Gombač, Klen Čopič Pucihar, Matjaž Kljun, Paul Coulton, and Jan Grbac. 2016. 3D Virtual Tracing and Depth Perception Problem on Mobile AR. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16)*. ACM, New York, NY, USA, 1849–1856. DOI: `http://dx.doi.org/10.1145/2851581.2892412`
16. Tovi Grossman and Ravin Balakrishnan. 2005. The Bubble Cursor: Enhancing Target Acquisition by Dynamic Resizing of the Cursor's Activation Area. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '05)*. ACM, New York, NY, USA, 281–290. DOI: `http://dx.doi.org/10.1145/1054972.1055012`
17. Tovi Grossman and Ravin Balakrishnan. 2006. The Design and Evaluation of Selection Techniques for 3D Volumetric Displays. In *Proceedings of the 19th Annual ACM Symposium on User Interface Software and Technology (UIST '06)*. ACM, New York, NY, USA, 3–12. DOI:`http://dx.doi.org/10.1145/1166253.1166257`
18. Jan Gugenheimer, David Dobbelstein, Christian Winkler, Gabriel Haas, and Enrico Rukzio. 2016. FaceTouch: Enabling Touch Interaction in Display Fixed UIs for Mobile Virtual Reality. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 49–60. DOI: `http://dx.doi.org/10.1145/2984511.2984576`
19. Carl Gutwin, Andy Cockburn, and Nickolas Gough. 2017. A Field Experiment of Spatially-Stable Overviews for Document Navigation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 5905–5916. DOI: `http://dx.doi.org/10.1145/3025453.3025905`
20. Sandra G Hart and Lowell E Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. *Advances in psychology* 52 (1988), 139–183.
21. Doris Hausen, Aurélien Tabard, Attila von Thermann, Kerstin Holzner, and Andreas Butz. 2013. Evaluating Peripheral Interaction. In *Proceedings of the 8th International Conference on Tangible, Embedded and*

Embodied Interaction (TEI '14). ACM, New York, NY, USA, 21–28. DOI: `http://dx.doi.org/10.1145/2540930.2540941`

22. Eric A Johnson. 2010. A study of the effects of immersion on short-term spatial memory. (2010).
23. Hannes Kaufmann, Dieter Schmalstieg, and Michael Wagner. 2000. Construct3D: a virtual reality application for mathematics and geometry education. *Education and information technologies* 5, 4 (2000), 263–276.
24. Arun Kulshreshth and Joseph J. LaViola, Jr. 2016. Dynamic Stereoscopic 3D Parameter Adjustment for Enhanced Depth Discrimination. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 177–187. DOI:`http://dx.doi.org/10.1145/2858036.2858078`
25. Frank Chun Yat Li, David Dearman, and Khai N. Truong. 2009. Virtual Shelves: Interactions with Orientation Aware Devices. In *Proceedings of the 22Nd Annual ACM Symposium on User Interface Software and Technology (UIST '09)*. ACM, New York, NY, USA, 125–128. DOI: `http://dx.doi.org/10.1145/1622176.1622200`
26. Frank Chun Yat Li, David Dearman, and Khai N. Truong. 2010. Leveraging Proprioception to Make Mobile Phones More Accessible to Users with Visual Impairments. In *Proceedings of the 12th International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '10)*. ACM, New York, NY, USA, 187–194. DOI: `http://dx.doi.org/10.1145/1878803.1878837`
27. David Lindlbauer, Klemen Lilija, Robert Walter, and Jörg Müller. 2016. Influence of Display Transparency on Background Awareness and Task Performance. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 1705–1716. DOI: `http://dx.doi.org/10.1145/2858036.2858453`
28. Pedro Lopes, Alexandra Ion, Willi Mueller, Daniel Hoffmann, Patrik Jonell, and Patrick Baudisch. 2015. Proprioceptive Interaction. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 939–948. DOI: `http://dx.doi.org/10.1145/2702123.2702461`
29. Moffat Mathews, Madan Challa, Cheng-Tse Chu, Gu Jian, Hartmut Seichter, and Raphael Grasset. 2007. Evaluation of Spatial Abilities Through Tabletop AR. In *Proceedings of the 8th ACM SIGCHI New Zealand Chapter's International Conference on Computer-human Interaction: Design Centered HCI (CHINZ '07)*. ACM, New York, NY, USA, 17–24. DOI: `http://dx.doi.org/10.1145/1278960.1278963`
30. George A Miller. 1956. The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological review* 63, 2 (1956), 81.
31. Diederick C Niehorster, Li Li, and Markus Lappe. 2017. The Accuracy and Precision of Position and Orientation Tracking in the HTC Vive Virtual Reality System for Scientific Research. *i-Perception* 8, 3 (2017), 2041669517708205.
32. Simon T. Perrault, Eric Lecolinet, Yoann Pascal Bourse, Shengdong Zhao, and Yves Guiard. 2015. Physical Loci: Leveraging Spatial, Object and Semantic Memory for Command Selection. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 299–308. DOI:`http://dx.doi.org/10.1145/2702123.2702126`
33. Ivan Poupyrev, Mark Billinghurst, Suzanne Weghorst, and Tadao Ichikawa. 1996. The Go-go Interaction Technique: Non-linear Mapping for Direct Manipulation in VR. In *Proceedings of the 9th Annual ACM Symposium on User Interface Software and Technology (UIST '96)*. ACM, New York, NY, USA, 79–80. DOI: `http://dx.doi.org/10.1145/237091.237102`
34. George Robertson, Mary Czerwinski, Kevin Larson, Daniel C. Robbins, David Thiel, and Maarten van Dantzich. 1998. Data Mountain: Using Spatial Memory for Document Management. In *Proceedings of the 11th Annual ACM Symposium on User Interface Software and Technology (UIST '98)*. ACM, New York, NY, USA, 153–162. DOI:`http://dx.doi.org/10.1145/288392.288596`
35. Jeremy Scott, David Dearman, Koji Yatani, and Khai N. Truong. 2010. Sensing Foot Gestures from the Pocket. In *Proceedings of the 23Nd Annual ACM Symposium on User Interface Software and Technology (UIST '10)*. ACM, New York, NY, USA, 199–208. DOI: `http://dx.doi.org/10.1145/1866029.1866063`
36. David Small and Hiroshi Ishii. 1997. Design of Spatially Aware Graspable Displays. In *CHI '97 Extended Abstracts on Human Factors in Computing Systems (CHI EA '97)*. ACM, New York, NY, USA, 367–368. DOI: `http://dx.doi.org/10.1145/1120212.1120437`
37. Jeroen BJ Smeets and Eli Brenner. 2008. Grasping Weber's law. *Current Biology* 18, 23 (2008), R1089–R1090.
38. Frank Steinicke, Timo Ropinski, and Klaus Hinrichs. 2006. Object selection in virtual environments using an improved virtual pointer metaphor. *Computer Vision and Graphics* (2006), 320–326.
39. Monica Tavanti and Mats Lind. 2001. 2D vs 3D, implications on spatial memory. In *Information Visualization, 2001. INFOVIS 2001. IEEE Symposium on.* IEEE, 139–145.
40. Md. Sami Uddin. 2016. Use of Landmarks to Design Large and Efficient Command Interfaces. In *Proceedings of the 2016 ACM Companion on Interactive Surfaces and Spaces (ISS Companion '16)*. ACM, New York, NY, USA, 13–17. DOI:`http://dx.doi.org/10.1145/3009939.3009942`

41. Md. Sami Uddin, Carl Gutwin, and Andy Cockburn. 2017. The Effects of Artificial Landmarks on Learning and Performance in Spatial-Memory Interfaces. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 3843–3855. DOI: http://dx.doi.org/10.1145/3025453.3025497
42. Lode Vanacken, Tovi Grossman, and Karin Coninx. 2007. Exploring the effects of environment density and target visibility on object selection in 3D virtual environments. In *3D User Interfaces, 2007. 3DUI'07. IEEE Symposium on*. IEEE.
43. Daniel Vogel and Ravin Balakrishnan. 2005. Distant Freehand Pointing and Clicking on Very Large, High Resolution Displays. In *Proceedings of the 18th Annual ACM Symposium on User Interface Software and Technology (UIST '05)*. ACM, New York, NY, USA, 33–42. DOI:http://dx.doi.org/10.1145/1095034.1095041
44. Aileen Worden, Nef Walker, Krishna Bharat, and Scott Hudson. 1997. Making Computers Easier for Older Adults to Use: Area Cursors and Sticky Icons. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI '97)*. ACM, New York, NY, USA, 266–271. DOI: http://dx.doi.org/10.1145/258549.258724
45. Hans Peter Wyss, Roland Blach, and Matthias Bues. 2006. iSith-Intersection-based spatial interaction for two hands. In *3D User Interfaces, 2006. 3DUI 2006. IEEE Symposium on*. IEEE, 59–61.
46. Robert Xiao and Hrvoje Benko. 2016. Augmenting the Field-of-View of Head-Mounted Displays with Sparse Peripheral Displays. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 1221–1232. DOI: http://dx.doi.org/10.1145/2858036.2858212
47. Ka-Ping Yee. 2003. Peephole Displays: Pen Interaction on Spatially Aware Handheld Computers. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '03)*. ACM, New York, NY, USA, 1–8. DOI: http://dx.doi.org/10.1145/642611.642613
48. Shumin Zhai, William Buxton, and Paul Milgram. 1994. The &Ldquo;Silk Cursor&Rdquo;: Investigating Transparency for 3D Target Acquisition. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '94)*. ACM, New York, NY, USA, 459–464. DOI: http://dx.doi.org/10.1145/191666.191822