An Evaluation of Self-Avatar Eye Movement for Virtual Embodiment

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Fig. 1. Viewing a self-avatar in a virtual mirror: In the image on the left the eyes of the avatar are fixed with respect to the head, preventing the participant from moving their head while maintaining eye contact with their avatar's reflection. In the image on the right the avatar's eyes rotate, enabling the participant to maintain eye contact while moving their head.

Abstract—We present a novel technique for animating self-avatar eye movements in an immersive virtual environment without the use of eye-tracking hardware, and evaluate our technique via a two-alternative, forced-choice-with-confidence experiment that compares this simulated-eye-tracking condition to a no-eye-tracking condition and a real-eye-tracking condition in which the avatar's eyes were rotated with an eye tracker. Viewing the reflection of a tracked self-avatar is often used in virtual-embodiment scenarios to induce in the participant the illusion that the virtual body of the self-avatar belongs to them, however current tracking methods do not account for the movements of the participants eyes, potentially lessening this body-ownership illusion. The results of our experiment indicate that, although blind to the experimental conditions, participants noticed differences between eye behaviors, and found that the real and simulated conditions represented their behavior better than the no-eye-tracking condition. Additionally, no statistical difference was found when choosing between the real and simulated conditions. These results suggest that adding eye movements to self-avatars produces a subjective increase in self-identification with the avatar due to a more complete representation of the participant's behavior, which may be beneficial for inducing virtual embodiment, and that effective results can be obtained without the need for any specialized eye-tracking hardware.

Index Terms—Virtual embodiment, eye tracking, virtual characters, user studies

1 Introduction

In virtual embodiment scenarios the participant in an immersive virtual environment (VE) is presented with a co-located virtual representation of a body. Viewing this self-avatar from a first-person perspective via a head-mounted display (HMD) elicits in the participant the illusion that the virtual body is in fact their own body [14, 17]. A virtual mirror, in which the participant can view the reflection of their self-avatar, is often used to enhance the virtual-embodiment illusion [5], as is animating the virtual body by tracking the participant's movements [18].

One problem with current tracking methods for virtual embodiment is that they do not account for the participant's eye movements. The eyes of the self-avatar remain fixed with respect to the avatar's head, such that when the participant moves their head they cannot maintain eye contact with their virtual reflection because the avatar's eyes will not return their gaze correctly. This discrepency between the eye-gaze direction of the participant and their virtual reflection does not occur with self-reflections in the real world–at no time have you looked at your eyes in a mirror to see them not looking back at you–and has the potential to interfere with the body-ownership illusion.

In this paper we present a two-alternative, forced-choice-with-confidence experiment, in which participants were blind to the experimental conditions, that compared three eye-tracking conditions in a virtual-embodiment scenario. The purposes of this experiment were to determine (1) if participants noticed any difference between the eye-tracking conditions, and (2) which of the conditions the participants felt was a "better representation" of their own behavior.

The three experimental conditions were no eye tracking (NET), real eye tracking (RET), and simulated eye tracking (SET). In the no-eye-tracking condition the self-avatar's eyes remained fixed with respect to

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the avatar's head, the current standard implementation for self-avatar representation. In the real condition the self-avatar's eyes were rotated using the rotation data from a monocular eye tracker mounted to the HMD (Section 3.2). In the simulated condition the self-avatar's eyes were rotated such that they always looked at their own reflection in the mirror without using any eye-tracking data, under the assumption that the participant should only notice the self-avatar's eyes when looking directly at their reflection in the virtual mirror (Section 3.3).

Our hypotheses were that real and simulated eye tracking would be preferred to no eye tracking, and that the preference of real vs. simulated eye tracking would depend on the quality of the eye-tracking data–good tracking data would enable the real method to capture subtle motions not captured by the simulated method, but tracking errors would cause the real method to exhibit inaccurate eye movements that would not occur with the simulated method.

Analysis of the forced-choice comparisons and questionnaire data from our experiment show that: 1) although blind to any differences in self-avatar eye behavior between conditions–participants were not told what the different experimental conditions were, nor how the avatar behaviors might differ–participants did notice differences in eye-behavior, 2) participants found that the real- and simulated-eye-tracking conditions exhibiting eye movements better-represented their behavior than the no-eye-tracking condition, and 3) no statistically significance difference was found between the real- and simulated-eye-tracking conditions.

These results indicate that adding eye movements to self-avatars can produce a subjective increase in self-identification with the avatar due to a more complete representation of the participant's behavior, which may be beneficial for inducing and maintaining body-ownership illusions. Additionally, effective results can be obtained using simulated eye tracking without the need for any specialized eye-tracking hardware, making the addition of self-avatar eye movements easily attainable for all virtual-embodiment scenarios.

2 Background

2.1 Virtual embodiment

Virtual embodiment is based in numerous fields, including cognitive neuroscience, philosophy of mind, and psychology [2]. By producing a strong ownership illusion over a virtual body, virtual embodiment is emerging as a useful tool in studies of body representation [25]. The ability to design and programmatically control the body representation supplied to participants enables various neuroscientific and psychological applications [1, 6, 7, 10].

Viewing a static self-avatar from a first-person perspective, with the ability to look down and see the virtual body in place of the real body, can induce an illusion of ownership over the virtual body, i.e. the perception that it appears to be "my body" [16]. Synchronous multisensory stimulation can enhance the illusion, such as visuo-haptic feedback where a virtual object seen to be touching the virtual body is correlated with the physical sensation of a real object touching the real body [13], a virtual mirror in which the participant can see the reflection of their self-avatar [5], and animating the self-avatar by tracking the participant's motions [12, 18].

This experiment investigates the incorporation of an additional multisensory stimulation, that of visuomotor correlation via self-avatar eye movements, to enhance the body-ownership illusion. Incorporating eye movements enables participant behaviors, such as maintaining eye contact with the reflection of their self-avatar while rotating their head, that were not previously possible and that could strengthen the body-ownership illusion.

2.2 Eye tracking for virtual reality and virtual characters

Eye tracking has been used for various purposes in VR, typically as a tool to determine where users are looking in a VE [3, 20]. Other work employs eye tracking to animate the eyes of virtual characters in real time, including avatars representing the participant [11, 15, 19, 23], and the statistical simulation of human eye behavior, such as saccades and blinking, based on eye-tracking data [9]. However, such work has thus far concentrated on animating the eyes of the participant's avatar *as seen by others*. We are aware of no other work that investigates the effect of the participant viewing the eye movements of the participant's *own self-avatar*. In our real-eye-tracking condition, all eye movements are captured directly and displayed to the participant, so statistically-generated movements are unnecessary (statistical models could potentially be investigated for improved filtering of eye-tracking data). For our simulated-eye-tracking method, incorporating statistically-generated eye movements that do not correspond to the participant's might increase avatar realism as viewed by a third party, but could reduce or break the embodiment illusion for the participant. Blinking is handled implicitly in all cases with a first-person avatar, as the participant's eyes close during blinks.

2.3 Visual perception

Our simulated-eye-tracking method is based on the variability of visual acuity across the visual field in humans. The visual acuity of the eye decreases rapidly with distance from the cone-rich fovea in the center of the eye. The fovea typically subtends a $1.5°$-$2°$ visual angle, with the central $0.5°$ of this region achieving the greatest visual resolution [24]. For reference, the thumbnail held out at arm's length subtends roughly $1°$ of visual angle.

Although the visual angle subtended by the reflection of a person's eye varies with distance from the reflected surface, the above numbers suggest that this visual angle should typically fit within the high-visual-acuity region of the fovea. From this observation we hypothesized that participants would only notice self-avatar eye movements when looking directly at the reflection of their avatar's eyes, and developed and evaluated the simulated-eye-tracking method described in Section 3.3.

3 System

3.1 Equipment and software

Participants viewed the VE via an NVIS nVisor SX111 wide-field-of-view HMD. This HMD has dual displays with 1280 x 1024 resolution and $76°$H x $64°$V fields of view (FOV) per eye, updated at 60 Hz. Each display is angled outward, with $50°$ horizontal overlap (66%), achieving a combined FOV of $102°$H x $64°$V. An Arrington Research ViewPoint EyeTracker attached beneath the right display of the HMD was used to track the right eye of each participant. This eye tracker works by tracking the pupil of the eye, illuminated by an infrared light. Head tracking was performed with a 6-degree-of-freedom Intersense IS-900 device. The VE was implemented in the XVR coding environment [22], using the HALCA [4] library to animate the two (one male and one female) virtual characters from RocketBox Studios.

3.2 Real eye tracking

Arrington Research's EyeTracker software was used for eye-tracker calibration and data capture in the real-eye-tracking condition. During calibration the participant looked at a series of 16 points displayed in a grid pattern in the right display of the HMD. This process produced a calibration grid visible to the experimenters that was used by the EyeTracker software to calculate the eye rotation. Default values were used for all eye-tracking parameters except smoothing, which was disabled because it was determined during pilots that errors due to loss of tracking when blinking were noticeable when smoothing was turned on–the bad data collected when blinking was averaged with the accurate data available after blinking. The greater the smoothing, the greater the lag in removing the bad frames from the current eye-rotation calculation.

Communication between the EyeTracker software and the VE was performed using VRPN [21]. The VRPN server and EyeTracker software communicated through a shared-DLL interface, and were run on the same computer as the VE to minimize eye-tracking latency. Because we used a monocular eye tracker, the same rotation was applied to each eye, resulting in parallel gaze direction for each eye (as with the other two conditions). Future work with a binocular eye tracker could investigate any effect from eye convergence or divergence.

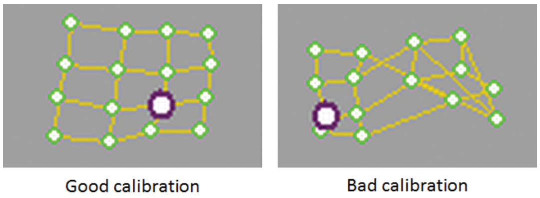

Fig. 2. Eye-tracker calibration grids. Participants with good eye calibration grids (e.g. left) were included in our data analysis. Participants with bad calibration grids (e.g. right) were excluded.

3.2.1 Pros

Assuming a good calibration and accurate eye tracking, the real eye tracking should provide the most accurate representation of the participant's eye motion, and could therefore provide the "gold standard" for self-avatar eye movements, e.g. enabling eye movements not captured by simulated eye tracking that might be visible when not looking directly at the reflection of the self-avatar's eyes. Similarly, future work could investigate capturing and rendering other features of the eye, such as pupil dilation or ocular torsion.

3.2.2 Cons

Although real eye tracking has the potential to provide the best representation of the participant's eye movements, it also has the potential to provide very unrealistic eye movements due to calibration or tracking errors. To obtain a good calibration the eye tracker had to be adjusted for each participant, independently manipulating the position and direction of the small eye-tracker camera and infrared light attached to the HMD. Difficulties due to the limited space between the eye tracker and the participant's eye often caused this process to be quite difficult, lasting up to 10 minutes. This difficulty was exacerbated due to the desire for good tracking at extreme eye rotations–participants often made large head rotations while maintaining eye contact with their self-avatar–and the immediate rendering of the eye-tracking data–no offline filtering methods could be used. Due to experience running pilots and recommendations from the literature [8] we included only participants who did not wear eye glasses or heavy eye makeup.

Even preemptively ruling out these potential participants, we were aware from pilots that we would probably not be able to obtain a good calibration for every participant due to factors such as facial structure, corrective lenses, and eye size, shape, and color. We therefore determined that upon calibration, if a good calibration grid was not produced–an obvious 4x4 grid with similar-sized squares and no overlapping nodes (Figure 2)–we would attempt another eye tracker adjustment and calibration, and if still unsuccessful we would mark the participant as not usable and exclude them from the data analysis presented here. Four out of sixteen participants were rejected in this manner. For participants with a bad calibration and bad tracking, the self-avatar's eyes exhibited obvious problems, such as jitter and fast rotations that did not correspond to the participant's eye movements.

3.3 Simulated eye tracking

Our simulated-eye-tracking method is a novel technique that mimics noticeable eye motion without the use of eye-tracking hardware. It is based on the fact that participants in a virtual-embodiment scenario should only notice eye movements when they are looking directly at the reflection of their self-avatar's eyes in a virtual mirror (Section 2.3).

When a self-avatar looks at its own reflection it is equivalent to looking perpendicular to the virtual mirror (Figure 3). Because the eyes have only two degrees of rotational freedom with respect to the head, the roll rotation of the head must also be applied to the eyes. We therefore multiply the one-dimensional roll rotation of the head and the two-dimensional pitch and yaw rotation necessary to look perpendicular to the mirror, and apply this combined rotation to the avatar's eyes. No eye-tracking data is necessary–only head-tracking data is used. Figure 4 shows how simulated eye tracking works for certain example head and and eye rotations.

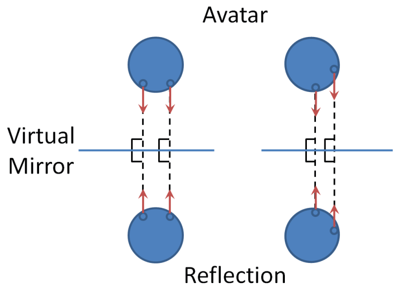

Fig. 3. Simulated eye tracking. Looking at one's reflection in a mirror is equivalent to looking perpendicular to the mirror.

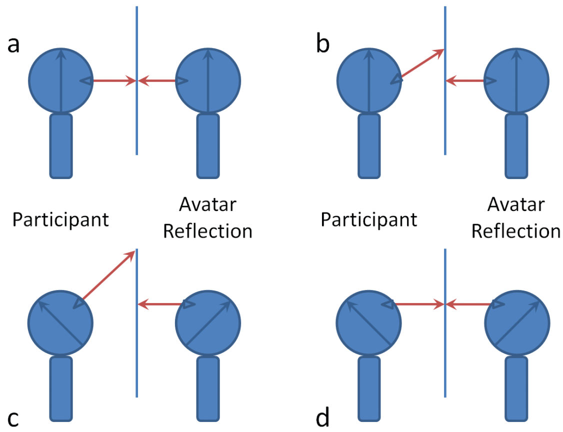

Fig. 4. Simulated eye tracking example. (a) Participant's head is level, looking at self-avatar eye reflection. Self-avatar's head is also level, eye rotation matches that of participant to return gaze correctly. (b) Participant keeps head level, but rotates eyes to look up. Self-avatar's head also remains level, with eye rotation perpendicular to mirror. Participant does not notice discrepancy in eye rotation because they are not looking at eye reflection. (c) Participant rotates head up and continues looking up with eyes. Self-avatar's head also rotates up to match participant's, and eyes rotate down to remain perpendicular to mirror. Participant still does not notice discrepancy in eye rotation. (d) Participant keeps head rotated up, but rotates eyes down to look at reflection. Self-avatar also keeps head rotated up and eyes perpendicular to mirror. Eye rotations now match, and participant notices that the avatar's reflection is returning their gaze correctly.

In our scenario we used one virtual mirror, calculating the eye rotation once per frame, but multiple mirrors could be added by rotating the avatar's eyes perpendicular to each mirror when rendering for that mirror. Computing this rotation for one eye and applying it to both eyes is equivalent to computing it separately for both eyes, as both result in view directions parallel to each other. Therefore, as with the monocular real-eye-tracking method (Section 3.2), convergence and divergence are not captured.

3.3.1 Pros

Simulated eye tracking does not require any additional eye-tracking hardware, and is therefore inexpensive and easy to use. It does not require any additional calibration setup per participant, and there is no need to exclude participants based on eye-tracking criteria. Simulated eye tracking is also more robust than real eye tracking–the avatar always looks at itself in the mirror, eliminating the possiblity of strange eye rotations due to eye-tracking errors.

3.3.2 Cons

The major disadvantage of simulated eye tracking is that eye movements that may otherwise be visible out of the corner of one's eye are not represented. It should also be noted that it is not suitable for VR applications in which the eye movements of the participant are to be conveyed to others, because the current view direction of the participant is not explicitly captured–it is only correct *for the participant* when they are looking *at their own virtual reflection*.

4 METHODS

4.1 Experimental design

Twelve participants (8 females and 4 males, average age with standard deviation 21 ± 2, and 27 ± 2 respectively), participated in this IRB-approved two-alternative forced-choice-with-confidence experiment comparing the no-eye-tracking (NET), real-eye-tracking (RET), and simulated-eye-tracking (SET) conditions. Each eye-tracking condition was compared to the other two eye-tracking conditions twice per participant, with presentation order reversed to account for order effects. The trial order was counterbalanced using Latin squares such that each of the three pairs of conditions was seen by each participant before any pair in the reverse order was seen. Additionally, the order of the presentation pairs was balanced to account for order effects, thus accounting for 12 different trial orders, one for each of the 12 participants.

4.2 Virtual environment

The VE consisted of a living room with a stool placed in front of a mirror, implemented using a stencil-buffer reflection technique. A male or female avatar corresponding to the gender of the participant was used. Participants were seated on a physical stool similar to and co-located with the one viewed in the VE. The self-avatar's head was rotated based on the head tracker, and although no explicit body tracking was performed, leaning backward, forward, and side-to-side, such that participants could look at their self-avatar more closely in the mirror, was enabled via a simple inverse kinematics method.

4.3 Procedure

4.3.1 Setup

Participants were given an information sheet and a consent form upon arrival to the laboratory. After completing the consent form they completed an online demographics questionnaire. Participants were then instructed to sit on the stool in the middle of the laboratory where they would stay for the remainder of the experiment.

Participants were instructed to place their hands comfortably on their legs, with their feet flat on the floor, unknowingly mimicking the posture of the virtual self-avatar. They were instructed that they could move their head and lean backward, forward, and side-to-side, but that they should remain seated and not move their hands or feet. They were told that they would be exposed to 6 pairs of different self-avatar behaviors, and for each pair asked to choose which behavior "was the best representation of yourself." At no point were the participants informed that there would be differences in how the avatar's eyes moved between the avatar behaviors.

After donning the HMD, eye-tracker calibration was performed.. Participants were informed that the eye tracker was a small camera for measuring pupil size. At no time prior to completing the experiment and questionnaire were they informed that it was in fact an eye-tracking device that might be used to animate the self-avatar's eyes.

After eye-tracker calibration the VE was displayed in the HMD. Participants were asked to look around to familiarize themselves with the environment and describe what they saw. During this phase no self-avatar was displayed so as to not expose them to any one of the eye-tracking conditions more than the others. The familiarization with the environment lasted for approximately one minute. The HMD then darkened, and participants were asked to look down toward their own body.

The VE was then displayed again, along with the self-avatar (Figure 5). Participants were asked to keep looking down toward their own body and again describe what they saw, such that they would be exposed to their self-avatar without seeing the reflection of the avatar's eyes. The HMD then darkened again, participants were told that they could look up, the instructions for the experiment explaining the block design and the focus question of which behavior "was the best representation of yourself" were repeated, and the experiment continued as described in the next section.

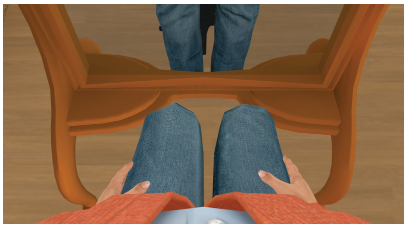

Fig. 5. Looking down at the self-avatar, with the avatar's legs reflected in the virtual mirror.

Beginning comparison	5 seconds
Situation 1	5 seconds
Participant interaction	30 seconds
Situation 2	5 seconds
Participant interaction	30 seconds
Which was the best representation of yourself?	Situation 1 or 2
What confidence do you have in your response?	Low, Medium, or High

x 6

Fig. 6. Diagram of a single block. There were six blocks per participant.

4.3.2 Experiment

The experiment consisted of six blocks of the following: "Beginning comparison" text screen; "Situation 1" text screen; 30-second exposure to an eye-tracking condition; "Situation 2" text screen; 30-second exposure to another eye-tracking condition; "Which was the best representation of yourself?" text screen; "What confidence do you have in your response" text screen. A diagram of each block is given in Figure 6. All participant responses were given verbally and recorded by the experimenters.

After the six blocks the HMD was removed from the participant, and they completed an online questionnaire. The total experiment time lasted for no more than one hour for each participant.

5 ANALYSIS

5.1 Forced-choice comparisons

Evaluation of the three different eye-tracking conditions (NET, RET, and SET) was performed via a two-alternative forced choice between each pair of conditions, with the metric for each choice being which condition the participant felt produced a better representation of their own behavior. Each pair of conditions was seen twice with order reversed such that each participant saw all six possible presentation orders.

For our analysis we first determined if there were any order effects in the presentation of the conditions since each participant experienced each pairing twice, but in a different order. This was counterbalanced amongst participants. For each condition pair we used a Wilcoxon signed-rank test to compare participants' forced-choices in one order compared to the opposite order, e.g. participants' forced choice between NET vs. RET compared to RET vs. NET. No presentation order effects were found for any condition pair, RET/NET: T=60, p=0.50, SET/NET: T=75.5, p=0.86, and RET/SET: T=66, p=0.75.

Similarly, no training effect was observed when comparing the first presentation of any eye-tracking condition pair, regardless of order, to the second presentation of that same eye-tracking condition pair, e.g. the first time participants chose between RET and NET, regardless of order, to the second time participants chose between RET and NET. The results from the Wilcoxon signed-rank tests for the three pairs were RET/NET: T=41, p=0.07, SET/NET: T=55, p=0.32, and RET/SET: T=70.5, p=0.95.

It is interesting to note the trend in the RET/NET condition when looking at training effect. The first time participants experience the RET/NET condition half of the participants chose RET over NET, however the second time participants experienced the RET/NET condition, 11 out of 12 participants chose RET over NET. This trend suggests that there may be a training effect in the RET condition where over time participants perceive that it produces a better representation of themselves. Future studies should further investigate this trend, however due to the lack of significance in order and training effects, the remainder of our analysis combines the results from both presentation orders of eye-tracking pairs.

For each comparison pair (NET/RET, NET/SET, and RET/SET) we compared the frequency at which participants preferred one eye-tracking condition over another to random chance, i.e. 50%, assuming that if one condition produced a better representation of the participant then the frequency of that condition being chosen over the other would be significantly greater than chance. Participants were also asked for the confidence of their decision (low, medium, or high). A weighted-forced-choice preference between each pair of conditions was calculated for each participant by mapping confidence levels low, medium, and high to values of 1, 2, and 3 respectively. For each pair of conditions, the difference in the total confidence between pairs was calculated and then normalized to a range of 0-100%, e.g. if a participant selected RET over NET with high confidence, and then NET over RET with low confidence, the weighted confidence of choosing RET over NET would be ((3 - 1) + 6) / 12 = 66.7%. Therefore when evaluating a pair of eye-motion conditions participants were only determined to have 100% confidence in that preference if one condition was chosen over the other with high confidence in both comparisons. The average weighted confidences for each eye-tracking comparison pair, with standard errors, is shown in Figure 7.

The weighted results are compatible with the hypotheses that for the RET/NET pair participants chose real eye tracking (mean = 66%) over no eye tracking (mean = 34%) by significantly more than chance, T=102, p=0.0339, and that for the SET/NET pair participants chose simulated eye tracking (mean = 69%) over no eye tracking (mean = 31%) by significantly more than chance, T=126, p=0.0007. The RET/SET pair's forced-choice results (mean = 45% and mean = 55% respectively) were not significantly different from chance, T=54, p=0.27, suggesting that the weighted forced-choice comparisons do not reject the null hypothesis–participants did not feel strongly that either real or simulated eye tracking better-represented their behavior compared to the other.

Similar results to the weighted evaluations were produced using the forced-choice data without weights. Using Wilcoxon signed-rank tests, the frequencies of participants' forced choices compared to chance show that the forced choices in the NET/RET and NET/SET pairs were significantly different from chance, T=108, p=0.0156, and T=108, p=0.0129 respectively. These results suggest that participants chose both real eye tracking (mean = 71%, 17 out of 24 trials (2 per participant)) over no eye tracking (mean = 29%, 7 out of 24 trials), and simulated eye tracking (mean = 75%, 18 out of 24 trials) over no eye tracking (mean = 25%, 6 out of 24 trials), by significantly more than chance. However the RET/SET pair's forced-choice results were not significantly different from chance, T=60, p=0.43, suggesting that participants did not feel strongly that either real (mean = 42%, 10 out of 24 trials) or simulated (mean = 58%, 14 out of 24 trials) eye tracking better-represented their behavior compared to the other.

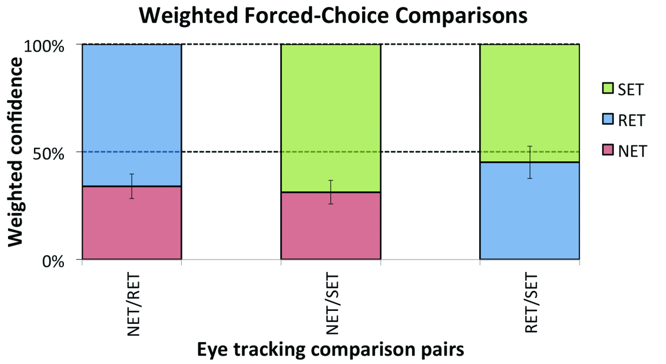

Fig. 7. The average weighted preference frequency, with standard error bars, of each eye-tracking condition for each of the pairs of eye-tracking conditions.

5.2 Questionnaire

Participants completed an exit questionnaire that asked them common embodiment questions and questions related to the eye-tracking conditions. The first two questions were about subjective sense of embodiment. On a 7-point Likert scale (1=strongly disagree, 7=strongly agree) participants were asked: 1) "I felt as if the body I saw in the virtual world might be my body" and 2) "I felt like the avatar was not me." Participants tended to affirm the illusion of body ownership, answering question with a high median (6 on the 1-7 scale) and relatively low IQR (2.25), suggesting that participants felt embodied in their virtual avatar despite the minimal motor contingencies (disgredaring the eyes) of only moving the head and upper body, and the frequent possible breaks in presence due to answering questions about the eye-tracking condition every 30 seconds. The sensation that the avatar was not me had median at the mid range (4) and higher IQR (3.25), suggesting that there was no tendency either way and higher variance with respect to this question.

In addition to the embodiment questions there were a series of questions attempting to determine whether participants realized that the avatar's eyes moved, and if they were able to distinguish between eye-tracking conditions. None of the questions mentioned the avatar's eyes.

When trying to describe the differences in the avatar's behavior 9 out of 12 mentioned the eyes. Three participants accurately described fixed eyes (no eye tracking) vs. eyes that moved, however no participants described the difference between simulated and real eye tracking.

When asked what behavior participants liked best, responses included "I liked the case where the avatar's eye movement corresponded to my eye movement for both eye(s)" and "...(when) the avatar was moving very much as I was, and when I looked at myself in the mirror I really had the sensation of being me, of looking at myself." When asked what behavior participants liked least, 6 out of 12 mentioned when the avatar's "eyes were fixed" or "staring at different places than me." No participant's stated least favorite behavior was when the avatar's eyes moved.

When asked what the avatar was doing when it "best represented you" all participants but one mentioned looking at itself in the mirror or that the eyes moved. Eight of 12 participants stated that the avatar was the worst representation of themselves when it would "look straight ahead" or "stare to a fixed point."

Finally, participants were asked: 1) "Did you notice that the avatar's eyes rotated differently in some of the conditions? (Yes, No)," 2) "Overall, which did you prefer? (The avatar eyes did not rotate, The avatar eyes did rotate)," 3) "Please explain your choice from the previous question," 4) "There were two different ways that the avatar's eyes rotated. Did you notice that there was a difference? (Yes, No)," and 5) "Describe, as best as possible, the difference between the two eye rotation conditions."

All twelve participants noticed that the avatar's eyes rotated differently in some of the conditions, and all but one participant preferred the conditions where the avatar's eyes did rotate compared to not rotating. When asked to explain their preference, one participant stated, "Eye rotation created a more accurate illusion which helped draw me into the virtual world." Interestingly, nine out of twelve participants said they noticed a difference between the two ways the avatar's eyes rotated, however their descriptions suggest that participants thought there were only two conditions, one where the eyes moved and one where they were fixed. Only one participant was able to discern that there were two different conditions where the eyes moved (real and simulated eye tracking) however they described the difference incorrectly: "I think that in one case both eyes were looking in the same direction constantly while in the second case each eye was moving independently."

6 Conclusion

We have presented a novel technique for animating self-avatar eye movements in virtual-embodiment scenarios without the use of eye-tracking hardware. This simulated-eye-tracking method takes advantage of the variable visual acuity of the human visual system to mimic only eye behavior that would be noticeable by the participant when looking at their virtual reflection. To evaluate our method we performed a two-alternative, forced-choice-with-confidence experiment comparing three different self-avatar eye behaviors, where participants were blind to the three conditions. Our simulated method was compared to a no-eye-tracking condition and a real-eye-tracking condition, in which the avatar's eyes were rotated using an eye tracker attached to the HMD.

The results of the experiment indicate that participants noticed differences between eye behaviors, and found the real and simulated conditions to better-represent their behavior than the no-eye-tracking condition. No statistical difference in user preference was found between the real and simulated conditions.

Although real eye tracking has the possibility to more fully represent the eye movements of the participant, our simulated method holds the advantage that it does not require any additional hardware to use, and is therefore inexpensive and immune to any eye-tracking errors. Additionally, it can be easily implemented in any VR software system, does not require any additional calibration/setup time, and works well regardless of factors such as corrective glasses/lenses or eye size, shape, or color.

Although no significant difference was found between the real and simulated methods in our experiment, future work should investigate utilizing the full data available from a binocular eye tracker (e.g. eye convergence and divergence, pupil dilation, and ocular torsion) to determine if such subtleties have an effect on user preference. Regardless of the results of such work, however, our simulated-eye-tracking method improves the state-of-the-art in avatar representation for virtual embodiment, and should be easy to incorporate into any scenario involving virtual mirrors. Additional future work will involve incorporating and comparing eye movements with other techniques used to induce the body-ownership illusion, such as visuo-haptic feedback and full-body tracking.

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