Evaluation of Hands-free Teleportation in VR

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ABSTRACT

Teleportation is a popular locomotion technique that allows users to navigate beyond the confines of available tracking space with the smallest chance of inducing VR sickness. Users typically specify a teleportation destination by using a hand-held motion-sensing controller. However, for various reasons, it can be desirable or required to have a hands-free alternative to controller-based teleportation. We evaluate three different hands-free ways of teleporting with users selecting a destination using head gaze and activating teleport using: (1) eye-wink, (2) a mouth gesture, and (3) dwell. A user study with 20 participants compared all three techniques to controller-based teleportation using a waypoint based navigation task. Quantitative and subjective results showed eye-wink is the most viable alternative to using a controller and offered a lower selection error.

1 INTRODUCTION

The ability to move around freely is considered one of the most appealing features of 3D applications. Navigating in VR without inducing VR sickness has remained a major challenge [34]. Walking input using positional tracking generally offers the highest presence [32], but it is difficult to scale beyond the confines of tracking limitations (outside-in tracking) or limited physical space (inside-out tracking). For exploring large VR environments, users must switch to an alternative locomotion technique (ALT). Some example ALTs include: walking-in-place, arm swinging, continuous locomotion, treadmills, etc (see [34] for a survey). A problem with some ALTs like full locomotion is that it generates optical flow without vestibular and proprioceptive afferents. This confuses the senses and can lead to vection-induced VR sickness [7, 32]. Teleportation discontinuously translates a user's viewpoint and thus avoids optical flow generation that could induce vection induced VR sickness [4]. Typically, VR requires the use of mid-air arm interactions using controllers. Prolonged use of mid-air interactions, e.g. when pointing with a controller to a destination to teleport to, could lead to arm fatigue [23]. Though teleportation is widely used in current VR experiences, it requires overloading the hands with navigation functionality, which has been argued to increase cognitive load and reduce efficiency [20]. Using hands for navigation interferes with other forms of time critical interactions that are most natural to hands (i.e., firing a gun, opening a door, picking up and holding an object). In the future, controllers could disappear in favor of more immersive forms of interaction enabled using hand tracking, which is already available on many VR Head Mounted Displays (HMD) that rely on inside-out tracking. Hands-free teleportation would alleviate the use of hands and arms and offer additional benefits in terms of accessibility, as some users may not be able to use a controller because of a disability [12]. This paper evaluates three hands-free teleportation methods and compares their performance in terms of efficiency, accuracy and usability to controller-based teleportation.

2 BACKGROUND

A comprehensive review of teleportation improvements and studies that benchmark teleportation to other ALTs can be found here [2]. We discuss teleportation techniques most closely related to this paper in that they are handsfree. LaViola et al. [20] presented a version of teleport where users step into a location on a map that is rendered at their feet in order to teleport to that location. Jumper [6] is a hands-free form of teleportation where users physically jump forward to a location specified by their head gaze in order to take a giant virtual leap forward. A user study with 11 participants found that though there was no difference in performance with natural walking and teleport, jumping was easier to learn than teleport but spatial orientation was worse than using natural walking. Jumper requires positional tracking. Kruse et al.[17] also explored jumping but used a positional difference along the vertical axes to trigger teleportation. A user study with 25 participants found using a controller to select a destination when jumping while standing offered the highest efficiency and usability and lowest VR sickness. Point and teleport [8] modified regular teleportation such that users could specify their post-teleport orientation. This approach does not require a controller but tracks the user's hands to allow for a raycast, so technically it is hands-free but still requires arms. Similarly, Schafer et al.[28] explored one and two handed gestures for teleport based locomotion and concluded that both are viable options for effective navigation. Høeg et al.[16] on the other hand found that users generally preferred using a button activated teleportation as opposed to either jumping or a fist clenching gesture that was detected using electromyography (EMG). Gaze teleportation [22] lets the user select a destination using eye gaze and initiate teleportation using a button. Eye gaze performance was found to be comparable to using a controller and had a higher user preference. However, the study had users teleporting to predefined targets which reduced the need for accurate eye gaze tracking.

Most studies with eye gaze have focused on using it for target selection rather than locomotion. Pai et al.[26] explored the use of eye gaze tracking with EMG on a user's forearm. A user study compared this input to gamepad, motion controller, head gaze with dwell time, and eye gaze with dwell time. Their study showed the viability of using eye gaze, but also pointed out its limitations. Blattgerste et al.[5] found eye gaze to have advantages over head gaze in terms of speed, task-load, head-movement and user preference but pointed out tracking problems with eye gaze. A study by Minakata et al. [25] found head gaze to outperform eye gaze in terms of speed and throughput. Similarly, Heydn et al.[14] and Qian et al.[27] found head gaze to be preferable over eye gaze. The most notable limitations of eye gaze reported in the literature are calibration inaccuracy, user compatibility, and HMD slippage. Finally, although to a lesser extent, mouth gestures have been suggested as a viable hands-free interaction technique. Most relevant to our study is De Silva et al.[10], where they proposed a mouth opening gesture as a hands-free alternative to using a mouse button click.

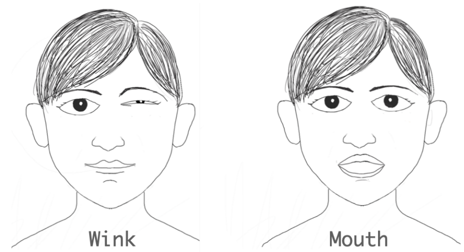

Figure 1: Wink teleport is activated by winking one eye (either left or right). Mouth teleport is activated by opening the mouth

3 DESIGN OF HANDS-FREE TELEPORTATION

Generally, teleportation consists of the following two distinct tasks: (1) selecting a location to teleport to; and (2) activating the teleport. Assuming that in most VR applications, users engage in grounded navigation (e.g., not flying) having to select a surface coordinate (X,Y) requires at least 2 degrees-of-freedom (DoF) input. As stated previously, eye gaze has been previously explored for VR target selection or text entry [24]. But its application has been limited to selection of predefined targets or keys, which unlike selecting a destination to teleport to, doesn't require a high selection accuracy at arbitrary distances. There are significant concerns about the accuracy of eye gaze selection. This is not only due to calibration errors and drift of wearable eye-tracking sensors [3, 19] but also because eye gaze is naturally subject to involuntary eye movements (i.e., optokinetic nystagmus)[9]. Strategies to solve this problem include smoothing the eye gaze [22] (increases latency) or techniques like goal crossing [31] but the latter strategy requires using predefined targets, which is not feasible for navigation. Thus a more viable alternative for handsfree destination selection is head gaze. Additionally, to activate teleport without a controller, we explore the following three mechanisms:

- **Dwell** is the de facto selection technique for gaze input and requires users to fixate their gaze for a specified amount of time on a target or menu item to select it. Dwell time affects performance and accuracy as a low dwell time increases performance but may increase accidental teleports.
- **Wink** or blink detection can be done reliably using an eye tracker. Electrooculography (EOG) has also been reported as a viable approach to detect eye blink/wink ([29],[18],[33]). Using wink (closing one eye) instead of blink (closing both eyes) reduces the possibility of false positives from natural eye blinks and avoids blocking the user vision while activating teleport.
- **Mouth** gestures can be recognized using a facial tracker. Preliminary trials with various gestures found that a simple mouth opening gesture (i.e., saying 'AA') worked best. In social environments, opening the mouth may be considered awkward but VR is still mostly used in private environments, so we believe this is not a major concern.

The choice of wink and mouth was motivated by the fact that the required sensors are increasingly becoming available on consumer VR headsets and thus would be more accessible as time goes on.

In a preliminary study Walker et al.[30]), in addition to dwell and blink, explored two other techniques, i.e., voice input and foot stomp (detected using an accelerometer). Techniques were implemented on Google Daydream HMD but due to technical constraints, Blink was implemented using the Fove HMD with integrated eye tracker. A user study with 16 participants found that foot stomp led to a high error rate and a low selection accuracy due to unintentional movements of the HMD when the user stomped their feet. Voice input (i.e. "Go") was implemented using a specific word "Go". But it was found to be rather slow and had a relatively high number of false negatives. Because VR is increasingly used for social interactions, using voice might interfere with speaking with other VR users. Instead using a mouth-opening gesture as a trigger avoids this. Also, facial animation in a social setting can be implemented in a way so that the opening of the mouth when triggering a teleport doesn't appear on the avatar's face (e.g. by adding a minimal latency to reject mouth-opening gesture).

4 USER STUDY

The goal of our study was to evaluate the performance, accuracy, and usability of hands-free teleportation (wink/mouth/dwell) to controller-based teleportation.

4.1 Instrumentation

We used the HTC Vive Pro Eye HMD to implement all teleportation techniques. This HMD has a resolution of 1440 x 1600 pixels per eye at 90HZ and offers a 110 degree field of view. It features an integrated Tobii eye tracker and a facial tracker add-on enabled real-time lip tracking. The HMD was connected to a gaming laptop (Intel Core i7 3.8GHz 32GB RAM, NVIDIA's GTX 1070 8GB) to run the VR application. We developed our navigation environment in Unity 2021.2.13f1 using the SteamVR plugin version 2.7.3. We used SteamVR's teleportation system [1] as the base and modified it to develop the three handsfree teleportation techniques. We use a raycast controlled by head gaze to determine the reticle position on the ground.

The maximum distance for the ray cast was set to 15m as pointing precisely beyond it was found to be difficult in preliminary experiments. Our teleportation reticle was a green translucent circle and we did not use a visual arch to avoid obscuring the user's view. Since our study is constrained to grounded navigation, we only detect teleportation destinations at the intersections of the user's head gaze and the ground plane. This also largely circumvents accidental teleports associated with using dwell. The user can now keep looking arbitrarily in any direction without triggering a teleport as long as their gaze doesn't intersect the ground plane within a 15m distance.

For wink teleport, we explored different values for the duration that one eye needed to be closed to activate the teleport. We set it to a value of 170*ms* so that the teleportation activation action felt intentional to the users. This compromised between generating false positives and having to excessively wink. Additionally, a maximum eye openness value of 25% was used to detect wink and to filter out most false positives.

For mouth gesture teleportation, we found a value of 200*ms* to be ideal. In addition, we tried out different values and settled on using a value of 50% minimum mouth openness for teleportation activation in order to avoid accidental teleports that may happen when the user talks to other users.

Controller-based teleportation is usually implemented using a parabolic arc where the destination is determined by the intersection of the arc with the ground plane. However, to make it consistent with the hands-free techniques, we used a raycast shot from the front of the controller as opposed to a parabolic arc. Teleportation is activated by pressing the touchpad on the controller. For dwell, we experimentally found a dwell time of 1.5 seconds to work best. Additionally, because the gaze moves slightly due to involuntary head movements, even when the user isn't actively trying to move the teleport reticle, a 'dead-zone' was required to combat unintentional teleports. For this, a proximity threshold of 0.25m was used. We kept a running average of all gaze positions during the previous 1.5 seconds. Anytime the distance between this running average and the current gaze position exceeded the proximity threshold, we reset both the dwell timer and the running average.

4.2 Virtual Environment & Navigation Task

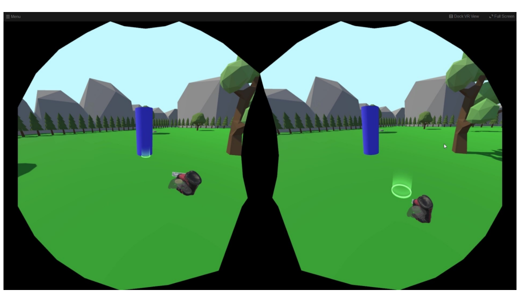

Figure 2: Virtual environment used for the user study. A blue column indicates a waypoint to navigate to. Right: a green circular teleportation pointer is visible. Left: user placing teleportation cursor on the waypoint.

Our VE consists of a low poly terrain peppered with low poly trees and mountain ranges. Participants were asked to perform a navigation task along a virtual path defined by a sequence of 24 waypoints. We used tall and distinctively colored (blue) cylindrical objects (1*m* radius) as waypoints to make them easy to spot and prevent them being occluded by trees. The distance between consecutive waypoints was predefined but randomly selected from the range 5-13m, which we deemed reasonable minimum and maximum distances a user would teleport. Participants were asked to go to each waypoint in order as quickly as possible using each method. Participants first targeted the waypoint and then activated teleport using the method being used. Upon activation, the virtual viewpoint is instantly teleported to the pointed location. If this location is within 1.40*m* from the center of the waypoint, the waypoint would disappear and a new waypoint would appear. If the teleport location is outside this radius, the participant would need to make another attempt to get closer to the waypoint. The trial would end once all 24 waypoints were reached.

4.3 Procedure and Data Collection

We used a within-subjects design with independent variable teleportation_method (i.e., controller, dwell, wink, mouth). To control for order effects, we counterbalanced the order of independent variables tested, e.g., each participant was randomly assigned to a group such that each group contained an equal number of participants (+ or - one participant). The order of what teleportation methods were used by each group was counterbalanced using a Latin square. To allow for comparison between methods, we used a predefined but randomly generated sequence of waypoints. The same sequence was used across all techniques and participants. Even though users could freely teleport to any location, they were tasked with following the sequence of waypoints. To minimize the possibility of participants memorizing the sequence from one method to the next, we changed the start position for each method and the order in which the waypoints were presented. The starting waypoint was randomly chosen for each technique and participants alternated traversal directions for each technique. User studies were held in a large open lab space free of any obstacles or interference. Prior to the trial, participants performed a brief built-in tutorial where each teleportation method was explained and participants had the chance to get comfortable with each technique. The whole trial took about 5 minutes per technique participant. Given the relative short duration of our study, there was no opportunity to measure arm fatigue of using a controller as this typically manifests itself only during prolonged VR interactions [15]. Quite a few studies found teleportation to not cause significant VR sickness [2]. Given that we only evaluated teleportation, we did not measure VR sickness nor fatigue. The primary goal was to compare the performance and accuracy of the proposed handsfree methods to using a controller. After the last trial, participants filled in a questionnaire that collected demographic information and which aimed to acquire qualitative feedback on each teleportation method, using a number of criteria.

To allow for a fair comparison between techniques, we decouple the visual search from the navigation task, e.g., if the lateral angle between the user's gaze pointer and the landmark is less than 40° for 0.75 seconds, we assume that the user can see the waypoint. For every waypoint, and for every teleport issued to get to each waypoint we collected: user location (2D), teleportation reticle location (2D), visual search duration (*s*). We calculate teleport travel time (*s*) by taking the total time for each task and subtracting the visual search time from it.

4.4 Participants

We recruited 20 participants (7 females, average age 24.3, SD=4.3, all undergraduate or graduate students) for our user study. All participants had experience with navigating 3D desktop environments.

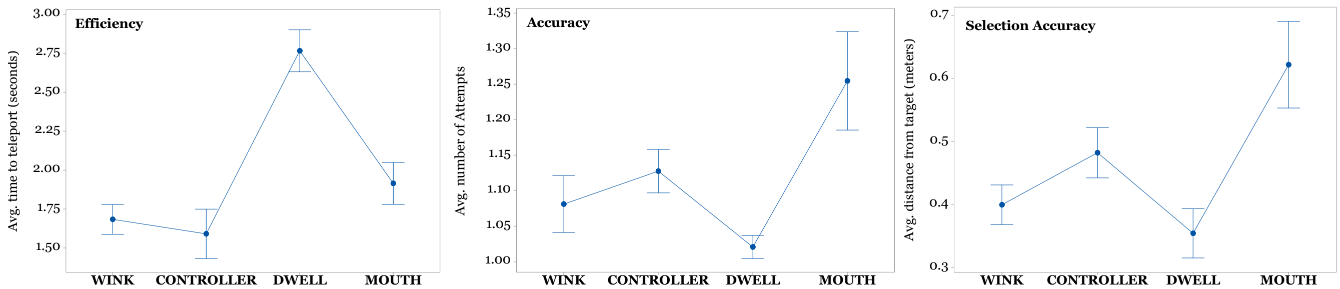

Figure 3: Efficiency, Accuracy and Selection error by technique. Error bar shows standard deviation.

None of the subjects self-reported any non-correctable impairments in perception or limitations in mobility. With regard to having used teleport in VR before, 4 had no experience, 5 had little experience, 2 had some experience, 6 had a moderate amount of experience, and 3 had lots of experience. The study was IRB approved and participants received a $10 gift card.

4.5 Results

For our comparative analysis we analyzed: (1) efficiency as the time to reach a waypoint (corrected for visual search time); (2) accuracy as the number of attempts made to reach a waypoint; and (3) selection error as the Euclidean distance between where the first teleportation cursor was placed and the waypoint that the participants needed to reach. If users used more than one teleport to get to the waypoint (e.g., when over or undershooting), we only used the data from the first teleportation they made to calculate this distance, since those following are assumed to be corrections. Going through

Pair	Efficiency	Accuracy	Selection Error
Controller-Wink	0.757	0.269	0.008
Dwell-Wink	0.000	0.031	0.288
Mouth-Wink	0.031	0.000	0.000
Dwell-Controller	0.000	0.000	0.000
Mouth-Controller	0.012	0.005	0.003
Mouth-Dwell	0.000	0.000	0.000

Table 1: p-values obtained from Games-Howell post-hoc test for efficiency, accuracy, and selection error.

the data, we found several data-points to have impossibly low teleportation times (range: 0.00-0.08 seconds). This only pertained to two users and was specific to eye-wink teleportation. We believe these errors were either caused by an eye tracking calibration error or a bug. Despite a large amount of preliminary testing these errors never occurred before. As a result, we decided to consider these observations (16 data points) to be outliers and we removed these from the data (1920 data points) before performing further analysis. Results are shown in Figure 3.

For efficiency, a test for equal variance showed that the variance differed significantly. A one-way Welch's ANOVA found a significant difference in the mean time to reach each waypoint for technique ($DF = 1038.56, F = 63.95, p = 0.00$). A post-hoc Games-Howell pairwise comparison found three groups [*Dwell*], [*Mouth*], and [*Wink, Controller*] with 95% confidence.

For accuracy, a test for equal variance showed that the variance differed significantly. A one-way Welch's ANOVA found a significant difference in the mean number of attempts users made to reach the waypoints for technique ($DF = 952.128.56, F = 24.07, p = 0.00$). A test for equal variance showed that the variance differed significantly. A post-hoc Games-Howell pairwise comparison found three groups *[Mouth]*, *[Controller, Wink]*, and *[Dwell]* with 95% confidence.

For selection error, a test for equal variance showed that the variance differed significantly. A one-way Welch's ANOVA found a significant difference in the mean Euclidean distance between waypoint position and first teleportation position ($DF = 1034.65, F = 18.22, p = 0.00$). A test for equal variance showed that the variance differed significantly. A post-hoc Games-Howell pairwise comparison found three groups *[Mouth]*, *[Controller]*, and *[Wink, Dwell]* with 95% confidence.

4.6 Subjective results

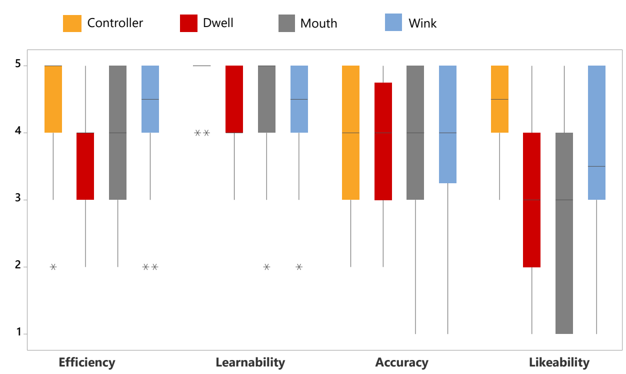

Figure 4: Columns show Likert scores (scale 1-5) as the median, the interquartile range, range, and outliers for each teleportation method based on the four criteria.

We asked users to rate each method they tested (including controller) in terms of efficiency, learnability, accuracy, likability using a 5 point Likert scale (with 1 being strongly disagree and 5 strongly agree). Usability is generally decomposed into these four attributes [11]. Questions were formulated as: *"Teleportation using a controller allowed me to navigate efficiently"* and *"Teleportation using wink was easy to learn"*. The results are summarized in Figure 4. A Friedman test found a significant difference in efficiency ($Q = 12.18, p = 0.007$), learnability ($Q = 14.05, p = 0.003$) and likability ($Q = 17.07, p = 0.001$). For efficiency, Nemenyi post-hoc test found a significant difference in Likert scores between controller and dwell ($p = 0.03$). For learnability, although Friedman test detected a significant difference, a post-hoc Nemennyi test couldn't identify any pairs with a statistically significant difference. For likeability, Nemenyi post-hoc test found a significant difference in Likert scores between controller and dwell ($p = 0.02$), and controller and mouth ($p = 0.002$).

5 DISCUSSION

We expected controller-based teleportation to be most efficient, accurate and have the highest usability, given that participants were most familiar with this type of input. We also expected dwell to be the slowest due to the dwell time. The results largely validated our assumptions that dwell was significantly slower than the other techniques. Because dwell has a minimum proximity threshold along with a minimum activation duration, it turned out to be relatively harder for users to use especially when trying to teleport to locations farther away. For this reason, even though the dwell time was set to 1.5s, on average the users ended up requiring around 2.76s to teleport. In terms of efficiency, there was no significant difference detected between wink and using a controller.

When it comes to accuracy, as measured by the number of attempts made to reach a way-point, dwell was most accurate. This was because dwell forced the user to take their time. There was no significant difference detected between using wink and a controller. The mouth gesture required significantly more attempts. During our experiment, we noticed users opened their mouths more than the required threshold we set (50%). In these cases, the HMD would nudge slightly upwards, and caused users to overshoot the target which resulted in a higher number of teleports.

In terms of selection error, we found that wink and dwell ended up performing the best, outperforming even a controller. Again, since dwell forced users to spend more time adjusting the reticle position, they spent more time being accurate. Wink on the other hand didn't have any such restrictions and thus outperformed using a controller which demonstrates that gaze selection generally has a higher level of accuracy. Mouth teleport performed the worst which was likely caused by small unintentional head movements from users opening their mouth. In real world VR usage, users are often not required to precisely teleport to a location, so having a small amount of selection error may not be a problem.

Subjective results partly confirmed quantitative results. In terms of efficiency, users felt that controller teleport was significantly more efficient than using dwell, likely because it took much longer. Although no significant difference between other techniques was detected, wink had an overall high score for efficiency. Learnability was high across the board for all techniques and the post hoc-test couldn't identify significant differences between any pairs.However, in terms of total score, controller was the highest. This is not surprising, given that most of our users had previous experience with using a controller in VR. Users also felt that the evaluated techniques offered a similar level of accuracy. Finally, in terms of likability, users preferred using a controller over both mouth and dwell teleport. While the median likability score for controller was higher than wink teleport, it didn't reach significance level. Users also liked using wink more than mouth.

6 FUTURE WORK

Our user study was subject to a number of limitations. Our implementation only considered teleporting at the ground level. In more realistic VR environments, users may be required to teleport to locations that vary in elevation. Allowing for such behavior would make dwell more susceptible to accidental teleports as they may get triggered even when their gaze is above the ground plane. A much longer dwell time might be required in such cases. Due to the relatively short duration of our experiment, we did not attempt to measure or assess arm fatigue as this manifests itself only over longer periods of usage and thus we make no claims that any of our techniques reduces arm fatigue. Although inability to wink bilaterally has been reported in the literature [21], none of our participants had any issue winking. Our implementation also allowed for choosing the preferred eye to wink with. To our knowledge, there aren't any studies showing the prevalence of total inability to wink.

Our study focused on navigation only and not simultaneously using a controller to perform other time critical actions. A prior study [13] compared hands-free locomotion techniques (i.e, head tilt and walking-in-place) to those activated by a controller (directional and teleport) while performing a bimanual task, but did not find a significant difference in performance. Based on our results, we are very interested in a comparison of using a controller versus using wink for teleportation while simultaneously requiring users to use their controller to interact with objects. A study over a longer period of time would allow for measuring arm fatigue and could reveal a significant advantage in terms of performance as well as alter users' subjective preference in favor of using a hands-free technique.

Our research results could help make VR more accessible for users with disabilities. Our study with able-bodied individuals provided useful insights into the effectiveness and usability of hands-free teleportation techniques but it would be important to compare the performance of wink and mouth gesture to gaze based teleportation that is activated with a button, since many users with severe motor impairments cannot use a controller but can often still use a button. Future user studies will include individuals with disabilities as able bodied participants cannot proxy for this demographic.

7 CONCLUSION

This paper evaluates three hands-free teleportation methods: dwell, eye wink, and mouth gesture to using a controller. A user study with 20 participants using a navigation task found no significant difference in performance between wink and a controller, with mouth and dwell both being significantly slower. Dwell required the fewest attempts with no difference between wink and using a controller. Eye wink and dwell both had the lowest selection error. Participants generally preferred a controller and wink teleport. Overall, results demonstrated wink to be a viable handsfree alternative to a controller, but requires a VR HMD with eye tracking.

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