Inter-Pupillary Distance Mismatch Does Not Affect Distance Perception in Action Space

Soumyajit Chakraborty
Vanderbilt University
Nashville, TN, USA
soumyajit.chakraborty@vanderbilt.edu

Hunter Finney
University of Utah
Salt Lake City, UT, USA
hunter@hunterfinney.com

Holly Gagnon
Vanderbilt University
Nashville, TN, USA
holly.gagnon@vanderbilt.edu

Sarah H. Creem-Regehr
University of Utah
Salt Lake City, UT, USA
sarah.creem@psych.utah.edu

Jeanine K. Stefanucci
University of Utah
Salt Lake City, UT, USA
jeanine.stefanucci@psych.utah.edu

Bobby Bodenheimer
Vanderbilt University
Nashville, TN, USA
bobby.bodenheimer@vanderbilt.edu

ABSTRACT

Most modern head-mounted displays (HMDs) do not support the full range of adult inter-pupillary distances (IPDs) (i.e., 45 – 80 mm) due to technological limitations. Prior work indicates that the mismatch between a user's actual IPD and the IPD set in the HMD ("IPD mismatch") can affect distance and size judgments in *near* space (0 – 2 m). Therefore, users with IPDs outside of the supported HMD IPD range may not perceive virtual environments (VEs) accurately. Across three experiments, we investigated whether IPD mismatch significantly affects peoples' distance judgments at longer distances (4 – 7 m). In two of the experiments, we recruited participants with IPDs smaller than the minimum supported IPD of the HTC Vive Pro HMD. They estimated distances in *action* space using verbal estimation (Experiment 1) and blind walking (Experiment 2) measures in indoor VEs. We found that: (i) distances were underestimated in *action* space, and (ii) IPD mismatch had minimal to no effect on their distance judgments. In a third experiment, we investigated whether we could generalize our findings to participants with an IPD within the supported HMD IPD range. We were able to replicate our previous findings. Overall, our findings suggest that IPD mismatch in an HMD may not be a major factor in distance underestimation in *action* space in VEs.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; *Empirical studies in HCI*; User studies.

KEYWORDS

Distance Perception, Inter-Pupillary Distance (IPD), Action Space, Verbal Estimation, Blind Walking

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1 INTRODUCTION

Inter-pupillary distances (IPDs; the distance between the centers of the pupils of the eyes) of adults range between 45 – 80 mm [Dodgson 2004]. However, most head-mounted displays (HMDs) do not support the complete range of IPDs because of technological limitations. As a result, users with an IPD outside of the supported IPD range will experience a mismatch between their actual IPD and the IPD set in the HMD. Females tend to have a smaller IPD distribution than males [Gantz et al. 2021], so there is a higher chance that more females have smaller IPDs than the supported minimum IPDs of several HMDs. IPD mismatch could be related to why females become more cybersick after experiencing a task in a virtual environment (VE) compared to males [Stanney et al. 2020]. Note, however, Doty et al. [2023] recently found no correlation between IPD and cybersickness among genders. To fix the IPD mismatch problem, some work has been done to compute and adapt the IPD of an HMD to a user's actual IPD [Kim et al. 2013; Robinett and Rolland 1992], but it is challenging to adapt an HMD to a user's IPD when their IPD is outside of the supported range.

Nonetheless, IPD mismatch can cause unnatural eye fixations, visual discomfort, and inaccurate depth perception. Specifically, users with smaller IPDs than the supported IPDs of an HMD overestimate distances, and those with larger IPDs underestimate distances in *near* to *action* space in a geometric quantification model [Hibbard et al. 2020]. Prior work indicates that people with different IPDs [Kim et al. 2013; Utsumi et al. 1994] or IPD mismatches in the HMD or CAVE [Renner et al. 2015; Tamura et al. 2024] exhibit differences in distance and size perception in *near* space (less than 3 m). This may be because IPD is crucial to generate better stereopsis, an important binocular depth cue, and as a result, manipulation of IPD could affect distance perception in near space. However, there may be smaller or inconsistent effects of IPD mismatch in *action* space (2 – 30 m) [Bruder et al. 2012; Willemsen et al. 2008] because binocular depth cues are not as effective at farther distances [Cutting and Vishton 1995]. The studies done in *action* space recruited participants with a wide range of IPDs (~50 – 70 mm), the mean IPDs were ~63 mm, which is the mean IPD of normal adults [Dodgson 2004] and is supported by most modern HMDs by default. Also, previous studies examining IPD effects used different techniques to measure distance judgments (such as virtual adjustment tasks [Kim et al. 2013; Renner et al. 2015; Utsumi et al. 1994], triangulated-walking [Willemsen et al. 2008], or a two-alternative force choice task [Bruder et al. 2012]).

In VEs presented by HMDs, distances are generally underestimated in *action* space (2 – 30 m) [Cutting and Vishton 1995] and beyond [Adams et al. 2022; Buck et al. 2021, 2018; Creem-Regehr et al. 2023; Kelly 2023; Rosales et al. 2019]. A recent meta-analysis [Kelly 2023] found that field-of-view (FOV), weight, and pixel density were technical factors of HMDs that contributed significantly to this underestimation, but there were still unexplained sources of variance. In their recent review of the literature, Creem-Regehr et al. [2023] suggest that IPD mismatch may be one of these unexplained sources of variance. This paper attempts to understand how much IPD mismatch might contribute to distance underestimation in VEs in *action* space. It is an important question given that the range of IPDs supported in most commercially available HMDs is a narrow subset of the range of IPDs that can be found in the population of potential users of HMDs.

Since many people have a smaller IPD than the minimum supported IPD of various commercially available devices, we investigated whether a mismatched IPD would affect their perception of distances in *action* space. We manipulated the mechanical IPD of an HMD to alter the IPD fitted to participants. We specifically recruited people with smaller IPDs than the minimum supported IPD of the HMD, which to our knowledge has not been done before. Participants estimated distances using verbal estimation (Experiment 1) and blind walking (Experiment 2), the two most common distance estimation methods [Creem-Regehr et al. 2023; Kelly 2023]. We found that IPD mismatch minimally affected distance judgments in action space. In Experiment 3, we investigated if we could generalize our findings to participants with an IPD supported by the HMD.

2 RELATED WORK

Perception of virtual environments can be inaccurate when a user has a different IPD than what is set in the HMD. As Bruder and Steinicke [2011] state: "A discrepancy between the user's IPD and stereoscopic rendering may distort the perception of the VE, since objects may appear minified or magnified." Interestingly, participants in their study preferred setting a smaller IPD for a small field of view (FOV) and a larger IPD with a larger FOV. In a different study, Bruder et al. [2012], found that participants perceived the size of a life-size human avatar in *action* space to be smaller than its original size while viewing it with a larger IPD. *Action* space is defined as distances up to 30 meters around a user, otherwise thought of as the area in which one can 'act' [Cutting and Vishton 1995]. The perceived size of one's self and the perceived scale of the external world can also be affected by IPD mismatch when the size ratio between one's body and the external world is known [Mine et al. 2020]. Previous studies in *near* space (closer than 3 meters) and geometric quantification models found that larger IPDs or larger IPD mismatch tends to lead to underestimation of distances [Hibbard et al. 2020; Renner et al. 2015; Utsumi et al. 1994]. In contrast, Kim et al. [2017] found that IPD mismatch did not affect size judgments in *near* space when they manipulated users' eye height and set the IPD to a smaller value than their actual IPD. Similarly, Best [1996] suggests no influence of IPD on size judgments of 2D objects in *near* space; it only affected the user's comfort. However, Kim et al. [2017] also found that participants underestimated the perceived sizes of cubes in *near* space when they experienced a larger IPD in the HMD.

In contrast to the mixed findings of the effects of IPD on size judgments, it is clear that IPD can affect distance perception in *near* space. For example, Utsumi et al. [1994] found that larger IPDs resulted in a significant underestimation of depth between 70 - 90 cm. Similarly, Renner et al. [2015] found that participants overestimated distances with smaller IPD but underestimated distances with larger IPD in a CAVE where the actual distances of the objects varied between ~25 - 70 cm. However, the effect of IPD on distance perception in *action* space is different than in *near* space. Comparing the actual IPD of the participants with a fixed IPD of 65 mm, Willemsen et al. [2008] found no significant effect of IPD on perceived distances between 5 - 15 m. A similar result was found by Bruder et al. [2012] at distances between 4 - 8 m. A comprehensive review of the effects of IPD in VR can be found at [Gerschütz et al. 2019]. In the current study, we investigated whether we could replicate the findings that IPD mismatch does not affect distance judgments in *action* space for users who have smaller IPDs than the minimum supported IPD, as this population has not been specifically studied in previous research.

3 EXPERIMENT 1

In Experiment 1, we examined distance perception in participants with IPDs smaller than the minimum supported IPD of the HTC VIVE Pro HMD (supported IPD range: ~60.7 - 73.5 mm). Participants used verbal estimation to judge the distance to targets presented in *action* space. We were also interested in whether a smaller IPD mismatch would affect distance perception differently than a larger IPD mismatch. Therefore, participants experienced two IPD conditions (within-subjects). In the small IPD mismatch condition, the IPD was set to the minimum HMD IPD, and in the large IPD mismatch condition, the IPD was set to the maximum HMD IPD. Based on the prior work described in Section 2, we hypothesized that: **(H1):** Participants would underestimate distances in both IPD conditions, and **(H2):** The maximum IPD condition would lead to more underestimation of distances than the minimum IPD condition because of a greater IPD mismatch.

3.1 Equipment and Design

3.1.1 Hardware and Software. To reliably measure the actual IPD of a participant, we used an optical digital pupillometer (released by Hyanyu), a portable handheld device that can measure IPDs between 45 - 82 mm. Using this device, we measured the IPD of several people in our university community before the experiment. We asked those who had an IPD less than 61 mm to participate in our experiment (26 people). The HTC VIVE Pro has a resolution of 1440×1600 per eye and a refresh rate of 90 Hz. The field of view (FOV) is 110° and the weight is approximately 555 g. The HMD was tethered to a nearby Windows 10 desktop computer with an Intel Core i7-6700K CPU, which could run at a speed of 4 GHz. It had a memory of 32 GB and an NVIDIA GeForce GTX 1080 graphics card. The virtual environment was created using Unity Game Engine (version 2020.3.14f1). We also used one VIVE Pro hand controller to record the inputs from the participants inside the application.

3.1.2 The Virtual Environments. The VE consisted of two indoor office environments of asymmetrical dimensions. One room had a dimension of ~14.5 m × 12.5 m × 3.5 m (Environment 1), and the other had a dimension of ~12.5 m × 12.5 m × 3.5 m (Environment 2). We used two environments to allow for more trials per participant and to reduce memory effects. Ceiling point lights lit both rooms, and they were furnished with bookshelves with some boxes on the shelves, tables with or without computers on them, chairs, robotic machinery, some carpets on the floor, and other objects such as decorated pots, trays, etc. The assets were part of a package called "Free Sci-Fi Office Pack" from the Unity Asset Store. We furnished the two rooms in such a way that they did not look identical. There was a door between the two rooms, which always remained closed throughout the experiment. Figure 1 shows the birds-eye views of the two virtual rooms and two participant views while performing trials in Environment 1. Throughout the experiment, continuous white noise of sea waves was played through the headphones of the HMD so that participants could not hear anything else from the physical environment that might cue them to distances.

A white, horizontal guideline was rendered on the ground to represent the starting point. The starting point is where participants stood to make their distance judgments. There were two possible starting points in each environment. The starting points were located at the opposite ends of the rooms. Figure 1(a) and (b) show the Starting points A and B in Environment 1, respectively.

3.1.3 Stimuli and User Interface for Data Recording. Participants were asked to estimate the distance of a traffic cone placed at several distances in front of them. To mitigate learning effects, we changed the scale and color of the cone. The scale of the original traffic cone was: width = 0.64 m, height = 0.83 m, and depth = 0.64 m. For the experiment, the cone sizes were 0.3×, 0.4×, or 0.5× of the original scale so that the cone appeared at a more natural size. For cone color, the cone could appear as its original texture (shown in Figure 1), completely red, or completely black. The scale and color of the cone were determined pseudo-randomly for each trial to ensure that the same specifications of the cone in the previous trial could not follow a randomly chosen scale and color of the cone.

To record the verbal estimates, participants were shown a simple User Interaction (UI) interface consisting of several buttons representing numbers from 0 – 9, a decimal point, "Backspace", and "OK" along with a text input field (to see their entered details) and a text field (that asked participants to estimate the distance of the traffic cone in their preferred units). The UI was presented at ~2.83 m from the virtual camera location with an angle of 45° from the virtual camera's forward axis. We placed the UI slightly off to the right of the participants in world space so that it did not hinder their judgments. Participants could interact with the virtual buttons with a virtual ray pointing out from a VIVE Pro hand controller and pressing the "Trigger" button. The UI was visible only when the participants indicated that they were ready to record their estimated distance by pressing the "Trigger" button on the hand controller after estimating the distance in the virtual rooms. Figure S1 in the supplemental materials shows a view of the UI.

3.2 Participants

We recruited 26 participants (5 males, 21 females) from our university community with an IPD smaller than 61 mm[1] (*min* = 55.5 mm, *median* = 58.5 mm, *max* = 60.5 mm, *M* = 58.42 mm, *SD* = 1.39 mm) between 18 - 70 years old[2] (*M* = 26.25 y, *SD* = 13.21 y). The sample size was inspired by prior studies [Best 1996; Kim et al. 2013; Renner et al. 2015; Utsumi et al. 1994] that investigated the effects of IPD or IPD mismatch on distance or size perception in *near* space. Our institution's IRB approved the protocol of all of the experiments in this paper. Participants gave their informed and written consent before the experiment started. At the end of the experiment, they were compensated 10 USD for their participation. All participants had no prior knowledge about the experiment and had self-reported normal or corrected-to-normal vision.

3.3 Procedure

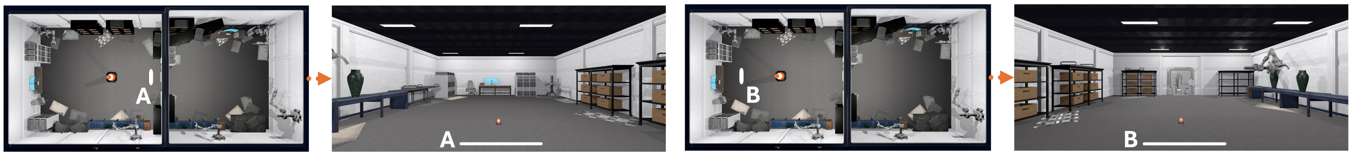
After consenting, participants were shown a distance of 1 m in the physical world using a tape measure. The experimenter verbally informed them about the converted units of 1 m in feet and yards (i.e., ~3.32 ft or 1.09 yd). Once familiar with this distance, the participant let the experimenter know their preferred unit of measurement for the experiment. Next, the experimenter helped the participant don the HMD to start the experiment. During this stage, the experimenter set the IPD of the HMD either to the minimum or to the maximum IPD. IPD condition order was counterbalanced across participants. The experimenter then recorded demographic information of the participants, including subject ID, age, gender, actual IPD, and the preferred unit of measurement by the participant in the program on the desktop computer. The participant was placed in either Environment 1 or Environment 2 and at one of the two possible starting points. Environment order and starting point order were counterbalanced across participants.

At the start of the first trial, participants were instructed to look down at their feet to see the horizontal guideline/starting point. Then, they looked at the presented traffic cone. Once they were ready to make their distance judgment, they pressed the trigger button on the controller. This button-press event turned the HMD screen black. The only virtual objects visible during this phase were the virtual representation of the hand controller, a green virtual ray pointed out of the virtual controller, and the UI interface. The participant entered their estimated distance (in their preferred unit of measurement) using the UI interface. Then, they selected the "OK" button in the interface to record the data and progress to the next trial.

Participants completed 13 trials during the first IPD condition in the first environment. The target distances of the first two trials in

[1]Although the HTC VIVE Pro can support an IPD of ~60.7 mm, we could not reliably set the IPD to exactly 60.7 mm due to the difficulty of rotating the HMD IPD dial. Therefore, we considered the minimum IPD of the HMD to be 61 mm. Similarly, we considered the maximum IPD of the HMD as 70 mm even though it could support an IPD up to ~73.5 mm.

[2]There were two participants of ages 69 and 70 years in this experiment. The mean proportional distance error of these participants did not fall outside of ±3 standard deviations of the young adult data, so we kept the older adult participant data in our analysis.



(a) (b)

Figure 1: Both left images of Figure 1(a) and (b) show the two rooms used in Experiment 1. The left room is "Environment 1" and the right is "Environment 2." The starting points "A" and "B" are shown in Environment 1. For each trial, the traffic cone was placed at a specific distance from the starting point. The size of the traffic cone is enlarged in the left images of Figure 1(a) and (b) for better visibility. The participant views (right images) show the traffic cone at 0.4× its original scale.

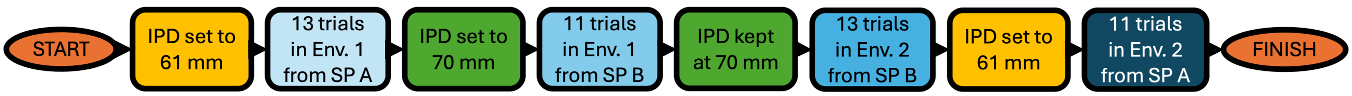


Figure 2: Possible sequence of executing the distance estimation task in Experiment 1 with verbal reports. "SP A" and "SP B" represent the starting points A and B. All participants' actual IPD was measured before running the experiment.

the first IPD condition were always 4.75 m and 6.25 m and served as practice trials. The remaining 11 trials consisted of 9 data trials at distances of 4 m, 5.5 m, and 7 m (each distance presented 3 times), plus two additional dummy trials of 4.75 m and 6.25 m. The trial order was the same predetermined sequence for all participants and arranged pseudo-randomly such that: (i) no two data or dummy trials of the same distance occurred back to back, and (ii) no dummy trials occurred at the end of the trial sequence. The dummy trials were not used in the analysis but were included only to mitigate learning effects.

Once participants completed the 13 trials of the first IPD condition in the first environment, they removed the HMD and were allowed to take a short rest before starting the second IPD condition. During this time, the experimenter adjusted the IPD accordingly. When ready, the participants donned the HMD and started the second IPD condition in the first environment. In the second IPD condition, participants were placed at the opposite starting point than what they experienced for the first IPD condition. Even though the virtual starting point was changed for the participants, they started the second IPD condition at the same physical location in the lab because the HMD was tethered to the nearby desktop computer. Participants completed 11 trials in the second IPD condition, similar to the first IPD condition: 9 data trials at distances of 4 m, 5.5 m, and 7 m (each distance presented 3 times), plus two dummy trials of 4.75 m and 6.25 m.

Once participants completed both IPD conditions in the first environment, they repeated the procedure, experiencing both IPD conditions in the second environment. In total, participants completed 48 trials (24 trials x 2 environments). After finishing all trials, the experimenter helped the participants remove the HMD, thanked them for participating, and provided compensation. A possible sequence of executing the distance estimation task in this experiment is shown in Figure 2.

3.4 Results

Distances entered into the UI interface were converted to meters. We calculated proportional distance error to assess the accuracy of the distance judgments. It is the ratio of the estimated distance to the distance of the traffic cone from the guideline. A ratio value of 1.0 represents perfect performance, whereas ratios greater or lesser than 1.0 indicate over- or under-estimation of distances, respectively. For analysis, participants' proportional distance errors were averaged by distance (4 m, 5.5 m, 7 m), IPD Condition, and Environment, resulting in twelve data points per participant.

For this experiment, we ran a 3 (Actual Distance) × 2 (IPD Condition) × 2 (Environment) within-subjects ANOVA on the mean proportional distance errors. Although we did not have a specific hypothesis about the environments, we included them in our analysis since they were explicitly manipulated, and it is possible that distance estimations could have been influenced by their slightly different configurations. If Mauchly's sphericity test was violated during the ANOVA analysis, Greenhouse-Geiser correction was automatically applied, and we report the corrected results. We also checked if our data met the assumption of normality. All analyses were performed in R using the $psych$, $performance$, $afex$, $emmeans$, and $BayesFactors$ packages.

Our data did not meet the assumption of normality (W = 0.99, p = 0.042). However, because the normality assumption was only marginally violated, we did not alter the data or analysis. There was a significant main effect of Actual Distance (F(1.12, 27.95) = 22.65, $p < 0.001$, $\eta_p^2 = 0.475$). Posthoc t-tests with Tukey's correction indicated that participants significantly underestimated distances (i) at 4 m (M = 0.658, SD = 0.15, SE = 0.026) compared to 5.5 m (M = 0.719, SD = 0.16, SE = 0.029, t(25) = -4.035, $p_{adjusted}$ = 0.001), (ii) at 4 m compared to 7 m (M = 0.760, SD = 0.18, SE = 0.032, t(25) = -5.019, $p_{adjusted} < 0.001$), and (iii) at 5.5 m compared to 7 m (t(25) = -5.496, $p_{adjusted} < 0.001$). Figure 3(a) shows these findings.

There was not a significant main effect of IPD Condition (F(1, 25) = 3.65, p = 0.068, η_p^2 = 0.127). Numerically, the Max IPD condition

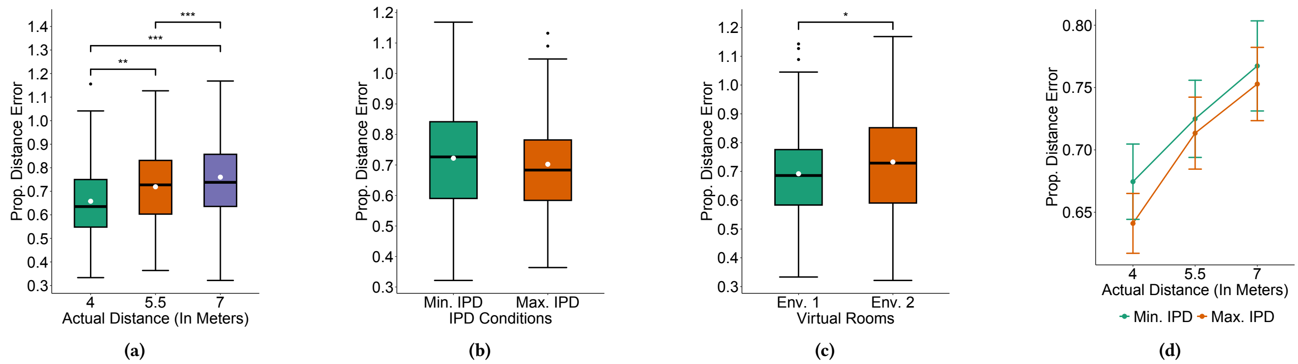


Figure 3: Experiment 1 main effects of (a) Actual Distance, (b) IPD Condition, and (c) Environment on proportional distance error (PDE) are shown. The white dots inside the box plots indicate the mean distance error. The *, **, and * on the significance bars in (a) and (c) represent significance levels of < 0.05, < 0.01, and < 0.001 respectively. Figure 3(d) shows PDEs for each IPD Condition by distance. Error bars in this figure represent ±1 standard errors of means.**

had slightly more error (M = 0.702, SD = 0.16, SE = 0.025) than the Min IPD condition (M = 0.722, SD = 0.18, SE = 0.031). There was a significant main effect of Environment ($F(1, 25) = 5.61$, $p = 0.026$, $\eta_p^2 = 0.183$). Participants underestimated distances significantly less in Environment 2 (M = 0.733, SD = 0.18, SE = 0.0314) compared to Environment 1 (M = 0.692, SD = 0.16, SE = 0.0270, $t(25) = -2.368$, $p = 0.0259$). None of the interactions were significant ($ps > 0.30$). Figure 3(b) and (c) show the main effects of IPD Condition and Environment on the Proportional Distance Errors.

Significant effects in frequentist statistics allow us to accept the alternative hypothesis over the null hypothesis. However, the lack of a significant effect does not mean we can accept the null hypothesis. Therefore, in order to seek evidence that there is *no* effect of IPD mismatch on *action* space distance perception, we conducted Bayes Factor analyses following Rouder et al. [2009]. Bayes factors provide an odds ratio (BF_{01}) that indicates support for the null over the alternative hypothesis. A BF_{01} of 1 indicates that the findings have a 50% chance to support the null hypothesis. However, if the $BF_{01} > 3$, > 10, or > 30, it shows that the findings are "somewhat likely", "moderately likely", or "very likely" in favor of supporting the null hypothesis. As Bayes Factors are highly sensitive to prior odds specification [Liu and Aitkin 2008], we set our prior odds to 1 so that the Bayes Factors had no weight favoring the null or alternative hypothesis [Buck et al. 2018].

Comparing the distance errors between the minimum IPD and the maximum IPD conditions, we found a BF_{01} of 0.685 (±0.02%), suggesting that there is no clear evidence supporting that the IPD conditions were significantly similar enough. So, we then compared the IPD conditions at each distance and found: (i) a BF_{01} of 0.4097 (±0.01%) between the minimum (M = 0.675, SD = 0.17, SE = 0.0302) and maximum (M = 0.641, SD = 0.14, SE = 0.0240) IPD at 4 m, (ii) a BF_{01} of 5.228 (±0.06%) between the minimum (M = 0.725, SD = 0.17, SE = 0.0309) and maximum (M = 0.713, SD = 0.16, SE = 0.0288) IPD at 5.5 m, and (iii) a BF_{01} of 3.646 (±0.05%) between the minimum (M = 0.767, SD = 0.20, SE = 0.0361) and maximum (M = 0.753, SD = 0.16, SE = 0.0294) IPD at 7 m. These findings suggest that the IPD conditions were somewhat likely to be similar enough at 5.5 m and 7 m. However, no clear evidence supported that the IPD conditions were significantly similar enough at 4 m. The result of the interaction between IPD Condition and Actual Distance is shown in Figure 3(d). We did not perform the Bayesian analysis on any other main or interaction effects, as our main interest was to investigate the effects of IPD mismatch at various distances in *action* space.

Overall, we found that people underestimated distances (total mean proportional distance error = 0.71), supporting our first hypothesis **H1**. The lack of a significant effect of the IPD Condition in the ANOVA suggests that there was no difference in distance judgments between the two conditions, which does not support our second hypothesis **H2**. However, the Bayesian analysis comparing the IPD conditions did not provide clear evidence that the IPD conditions performed the *same* (i.e., no clear evidence for the null hypothesis). There was some evidence that the IPD conditions might perform the same at 5.5 m and 7 m, but not at 4 m. Therefore, our results somewhat support the previous findings that IPD mismatch has minimal to no effect on distance perception in *action* space [Bruder et al. 2012; Willemsen et al. 2008].

We also found a significant effect of environment on the proportional distance errors judged using verbal estimation. Distances were underestimated less in Environment 2 compared to Environment 1. A possible explanation for this finding could be that the length of Environment 2 (12.5 m) is slightly shorter than Environment 1 (14.5 m). As a result, even though both rooms had similar objects around the walls, Environment 2 was more cluttered than Environment 1 which may have contributed to different distance estimations [Masnadi et al. 2022].

4 EXPERIMENT 2

Although convenient to implement, verbal reports are a more variable and noisy distance estimation measure compared to blind walking [Creem-Regehr et al. 2023]. Therefore, we used blind walking as the response method for Experiment 2 to see if we would get similar results as Experiment 1. Similar to Experiment 1, we were interested in examining distance perception for participants with a smaller IPD than the HMD IPD range. Participants made distance judgments to traffic cones presented at 4 m, 5.5 m, and 7 m using blind walking in two IPD conditions. In the minimum IPD condition, the HMD IPD was set to the minimum value (62 mm)[3]. In the maximum IPD condition, the HMD IPD was set to the maximum value (70 mm). We had the same hypotheses as in Experiment 1.

4.1 Equipment and Design

Due to inadequate physical space for blind walking in the lab used for Experiment 1, we conducted Experiments 2 and 3 in a different lab where participants could walk freely up to ∼10 m. Subsequently, we used a different HTC VIVE Pro HMD tethered to a different computer in that lab. The computer had an Intel Xeon W-2255 Processor, which could run at 3.7 GHz. It had 32 GB of memory and was installed with an NVIDIA RTX 3080 Graphics Card.

In Experiments 2 and 3, participants only experienced one virtual environment: Environment 1 from Experiment 1. We only used one environment in the blind walking experiments in order to minimize participant fatigue. In addition, the UI interface used in Experiment 1 was not used in Experiments 2 and 3 since participants estimated distance by blind walking.

4.2 Participants

Seventeen new participants (4 males, 13 females) with IPDs less than 62 mm completed Experiment 2 (IPD: *min* = 56.5 mm, *median* = 58.5 mm, *max* = 61.5 mm, M = 59.06 mm, SD = 1.48 mm). Participants were recruited from our university community and were 18 - 33 years old (M = 22 y, SD = 4.21 y). They gave informed consent and were compensated 10 USD for their participation.

4.3 Procedure

The procedure was similar to Experiment 1, except that participants estimated distance by blind walking to the perceived location of the target and only completed trials in Environment 1. Participants began the experiment after completing the consent process and entering demographic information. Before donning the HMD, subjects practiced blind walking once to a physical cone to get acquainted with the procedure. The trial design was the same as Experiment 1. For the first IPD condition, participants completed the two demonstration trials after performing the practice trial in the real world, followed by 11 experiment trials (9 data trials, 3 at each distance, and 2 dummy trials). In the second IPD condition, participants completed the 11 experiment trials. Participants completed a total of 24 trials. The order in which participants experienced the IPD conditions and the starting point locations was counterbalanced across participants.

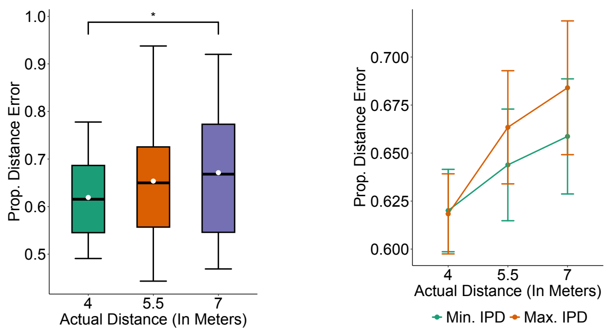
In each trial, after viewing the traffic cone, participants pressed the trigger button on the controller, which turned the HMD screen black. The participant was asked to physically walk to the estimated location of the target. Even though the HMD screen was black, participants were instructed to close their eyes. The experimenter always walked next to the participant to avoid any potential collisions with walls, objects, or other people in the lab. Once they reached the estimated distance, the participant pressed the trigger button on the controller to record the distance walked. The HMD automatically recorded the walked distance in meters. Then, the experimenter walked the participants back to the starting point in a zig-zag pattern so they could not get any body-based cues while walking back. The HMD screen remained black during this phase. Upon returning to the starting point, the experimenter turned the participant to face the same direction in the physical room they faced during the previous trial and asked them to press the trigger button on the controller to start the next trial. Markings on the floor out of view of the participant ensured that subjects always returned to the same position and orientation across trials. Figure S2 and Figure S3 in the supplementary materials show views of the blind walking procedure and a possible sequence of executing the distance estimation task in this experiment, respectively.

[3]We used a different HTC VIVE Pro in this experiment than the one used in Experiment 1 because we ran the experiment in a different lab. For this HMD, we considered the minimum IPD as 62 mm because that was the smallest number we could reliably set using the IPD wheel on the HMD.

4.4 Results

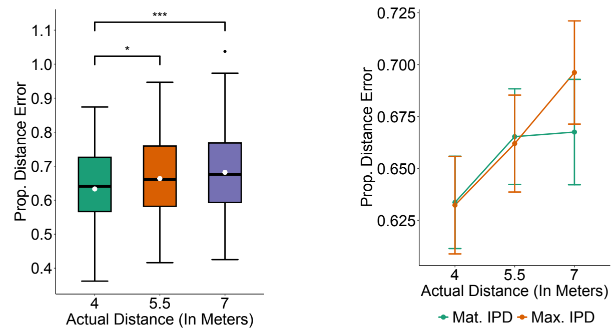
Proportional distance errors were analyzed using a 3 (Actual Distance) x 2 (IPD Condition) within-subjects ANOVA. Our data were normally distributed (Shapiro-Wilk test: $W = 0.98$, $p = 0.26$). There was a significant main effect of Actual Distance ($F(1.27, 20.32) = 5.5$, $p = 0.023$, $\eta_p^2 = 0.256$). However, posthoc t-tests with Tukey's correction only showed a marginal difference between the distance errors at 4 m ($M = 0.619$, $SD = 0.09$, $SE = 0.02$) and 7 m ($M = 0.671$, $SD = 0.13$, $SE = 0.0312$, $t(16) = -2.530$, $p = 0.0550$). There were no other significant or marginal differences between the other distances ($ps > 0.10$). No significant main effect of IPD Condition was found in our analysis ($p = 0.254$). There was no significant interaction between IPD Condition and Actual Distance either ($p = 0.292$). Figure 4(a) shows the main effect of Actual Distance on the proportional distance errors.

Similar to Experiment 1, we calculated Bayes factors in favor of the null hypothesis (BF_{01}) to examine whether there is evidence to support that the two IPD conditions were similar to each other. We found a BF_{01} of 2.08 (±0.04%) between the distance errors for the minimum IPD and the maximum IPD conditions. This finding shows no clear evidence to support the null hypothesis that distance errors in the minimum IPD condition were significantly similar to the maximum IPD condition. So, we compared the distance errors under each IPD condition at each distance and found: (i) a BF_{01} of 3.99 (±0.01%) between the minimum ($M = 0.620$, $SD = 0.09$, $SE = 0.0215$) and maximum ($M = 0.618$, $SD = 0.09$, $SE = 0.0209$) IPD at 4 m, (ii) a BF_{01} of 2.12 (±0.02%) between the minimum ($M = 0.644$, $SD = 0.12$, $SE = 0.0291$) and maximum ($M = 0.663$, $SD = 0.12$, $SE = 0.0295$) IPD at 5.5 m, and (iii) a BF_{01} of 1.74 (±0.02%) between the minimum ($M = 0.659$, $SD = 0.12$, $SE = 0.0300$) and maximum ($M = 0.684$, $SD = 0.14$, $SE = 0.0348$) IPD at 7 m. These findings suggest that the distance errors made in both IPD conditions were somewhat similar at 4 m. However, no clear evidence supported that the distance errors judged under both IPD conditions were significantly similar enough at 5.5 m and 7 m. Figure 4(b) shows the interaction between IPD Condition and Actual Distance.



(a) (b)

Figure 4: (a) Experiment 2 main effect of actual distance on proportional distance error (PDE). The white dots inside the box plots indicate the mean distance error. The * in this figure represents a marginal significance level of 0.055. (b) PDEs for each IPD Condition by distance. Error bars represent ±1 standard errors of means.



(a) (b)

Figure 5: (a) Experiment 3 main effect of Actual Distance on proportional distance errors (PDE). The white dots inside the box plots indicate the mean distance errors. The * and * in (a) represent significance levels of < 0.05, and < 0.001, respectively. (b) PDEs for each IPD Condition by distance. Error bars represent ±1 standard errors of means.**

Participants underestimated distances overall (total mean proportional distance error = 0.648), supporting our first hypothesis **H1**. Similar to Experiment 1, there was no effect of IPD Condition (not supporting **H2**), but the Bayes analysis was also inconclusive. There was some evidence that the distance underestimations by both IPD conditions might be similar at 4 m, but not at 5.5 m and 7 m. Therefore, our results somewhat support the previous findings that IPD mismatch has minimal to no effect on distance perception in *action* space [Bruder et al. 2012; Willemsen et al. 2008].

5 EXPERIMENT 3

In Experiment 3, we expanded our inclusion criteria to test whether those who *are* accommodated by the HMD compared to those who are not would also show the magnitude of distance underestimation observed in Experiments 1 and 2. It could be that people with small IPDs will generally underestimate distances in any IPD condition. To understand whether the magnitude of underestimation was due to the specific sample, we ran another experiment to test for underestimation across IPD conditions in those with normal range IPDs. We predicted that people within the HMD's IPD range would underestimate distances less than those outside the HMD's IPD range. We had two groups of participants (IPD Group): those with IPDs less than the minimum HMD IPD and those with an IPD within the HMD IPD range. We had two IPD conditions, similar to Experiments 1 and 2. In the matched/minimum condition, if the participant had an IPD within the range of the HMD, the IPD was set to their actual IPD. If the participant had an IPD less than 62 mm, the IPD was set to 62 mm. In the maximum IPD condition, the IPD was set to the maximum value (70 mm) for all participants. We used the same design and procedure as Experiment 2.

5.1 Participants

We recruited 33 new participants (11 males, 22 females) from our university community between 18 - 26 years old (M = 19.45 y, SD = 1.62 y) who either had an IPD less than 62 mm or an IPD between 62 mm and 70 mm. There were 13 participants with IPDs less than 62 mm (min = 56.00 mm, $median$ = 59.50 mm, max = 61.50 mm, M = 59.46 mm, SD = 1.51 mm). There were 20 participants with an IPD within the HMD IPD range (min = 62.00 mm, $median$ = 63.81 mm, max = 67.50 mm, M = 63.98 mm, SD = 1.59 mm). They gave informed consent and were compensated 10 USD for their participation.

5.2 Results

For Experiment 3, we ran a 3 (Actual Distance) x 2 (IPD Condition) x 2 (IPD Group) mixed ANOVA to analyze the proportional distance error. Actual Distance and IPD Condition were within-subjects variables and IPD Group was between subjects. The data met the assumptions of homogeneity (Levene's test: p = 0.825) and normality (Shapiro-Wilk test: W = 0.99, p = 0.226).

There was a significant main effect of Actual Distance ($F(1.74, 53.80) = 11.81$, $p < 0.001$, $\eta_p^2 = 0.276$). Posthoc t-tests with Tukey's correction showed that participants significantly underestimated distances at (i) 4 m (M = 0.633, SD = 0.13, SE = 0.022) compared to 5.5 m (M = 0.664, SD = 0.13, SE = 0.022, $t(31)$ = -3.12, $p_{adjusted}$ = 0.011), and (ii) at 4 m compared to 7 m (M = 0.682, SD = 0.14, SE = 0.023, $t(31)$ = -4.12, $p_{adjusted} < 0.001$). The difference between 5.5 m and 7 m was not significant (p = 0.097). Figure 5(a) shows the main effect of Actual Distance on the Proportional Distance Errors. There was no effect of IPD group. To examine possible effects of individual IPD differences in the matched/minimum condition, Pearson Correlations were run between Actual IPD and the proportional distance error for each HMD and gender group and showed no significant correlations. All other main effects and interactions were not significant ($ps > 0.27$).

Because we did not find a significant main effect of IPD Condition, we calculated Bayes factors in favor of the null hypothesis (BF_{01}) to investigate if there is any evidence to support that the distance errors in the two IPD conditions were similar to each other. We found a BF_{01} of 7.18 (±0.12%) between the distance errors during the matched and the maximum IPD conditions, suggesting that distance errors during the matched IPD condition were somewhat likely to be similar to the maximum IPD condition. We further compared the IPD conditions at each distance and found - (i) a BF_{01} of 5.36 (±0.04%) between the matched (M = 0.634, SD = 0.12, SE = 0.0222) and maximum (M = 0.632, SD = 0.13, SE = 0.0235) IPD at 4 m, (ii) a BF_{01} of 4.96 (±0.04%) between the matched (M = 0.665, SD = 0.13, SE = 0.0230) and maximum (M = 0.662, SD = 0.13, SE = 0.0233) IPD at 5.5 m, and (iii) a BF_{01} of 2.66 (±0.03%) between the matched (M = 0.668, SD = 0.14, SE = 0.0254) and maximum (M = 0.696, SD = 0.14, SE = 0.0249) IPD at 7 m. These findings suggest that the IPD conditions were likely to be similar enough at 4 m and 5.5 m. However, no clear evidence supported that the IPD conditions were significantly similar enough at 7 m. Figure 5(b) shows the interaction between IPD Condition and Actual Distance.

We also computed a Bayes Factor to compare the Below Minimum (M = 0.659, SD = 0.13, SE = 0.0335) and Within Range (M = 0.660, SD = 0.14, SE = 0.0270) IPD groups to investigate if their mean distance errors were significantly similar enough. We found a BF_{01} of 6.33 (±0.06%) between these two groups, which provides evidence that the two IPD groups were somewhat likely to exhibit the same judgments. As the groups were not the same size, we report the 95% credible interval (0.642, 0.677) within which range the true Bayes Factor will likely fall given the observed data.

These results show that participants underestimated distances (total mean proportional distance error = 0.66), supporting hypothesis **H1**. Once again, there was no effect of IPD Condition in the ANOVA, not supporting **H2**. The results of the Bayes analysis indicated that there was some evidence that the distance underestimations by both IPD conditions were somewhat similar at 4 m and 5.5 m, but not at 7 m. Thus, our results support the previous findings that IPD mismatch has minimal effect on distance perception in *action* space [Bruder et al. 2012; Willemsen et al. 2008].

In this experiment, participants either had an IPD that was smaller than 62 mm or an IPD that was within the supported range of 62 mm – 70 mm. The lack of a significant effect of IPD group suggests no difference between distance judgments between the two groups. However, the Bayesian analysis comparing the IPD groups provided only some evidence that the distance errors performed by both IPD groups were similar. This finding suggests that IPD mistmatch may not be a crucial factor affecting distance judgments in *action* space.

6 DISCUSSION

This paper investigated the effects of IPD mismatch on distance perception in *action* space. Because many people have smaller IPDs than the minimum supported IPD of an HMD, we recruited participants with smaller IPDs than the minimum IPD supported by the HTC VIVE Pro. In Experiment 3, we investigated whether we could generalize our findings from Experiments 1 and 2 to participants with an IPD within the supported IPD range of the HMD. In all experiments, participants completed two IPD conditions. In Experiments 1 and 2, in the minimum IPD condition, the HMD IPD was set to the minimum value, resulting in a smaller mismatch between participants' actual IPD and the set IPD. In the maximum IPD condition, the HMD IPD was set to the maximum supported IPD, which resulted in a large mismatch between participants' actual and set IPDs. In Experiment 3, for participants with IPDs below the supported minimum IPD, the minimum IPD condition was the same as the first two experiments. If the participant had an IPD in the supported range, the IPD was set to their actual IPD.

We found that participants underestimated distances overall in *action* space in every experiment. This is a common finding, shown in many previous studies [Creem-Regehr et al. 2023; Kelly 2023]. Distances were underestimated more in Experiments 2 and 3 (blind walking) than in Experiment 1 (verbal estimation). However, the amount of underestimation we found in our blind walking experiments was similar to that of Buck et al. [2021], which examined *action* space distance perception using the same HMD (HTC VIVE Pro) and response measure (blind walking) that we used. In Buck et al., participants estimated distances to targets presented at 5 m, 7.5 m, and 10 m in an outdoor environment, and the total mean proportional distance error was 0.60. Even though Buck et al. did not manipulate IPD, we found a similar magnitude of underestimation (0.65 in Experiment 2 and 0.66 in Experiment 3). It is possible that our experiments exhibited slightly less underestimation compared to Buck et al. because indoor environments can provide more reference cues than outdoor environments, resulting in more accurate distance perception [Creem-Regehr et al. 2023; Masnadi et al. 2022].

The lack of a significant effect of the IPD condition in each experiment suggests no difference in distance judgments between the two conditions. The Bayesian analysis provided some evidence that the distance errors of the two conditions were similar in Experiment 3. However, there was no clear evidence that the distance errors of the conditions were similar in Experiments 1 and 2 except when comparing at certain individual distances. Further research should be conducted in order to draw a stronger conclusion, likely with a larger sample size. Thus, it appears that IPD mismatch does not influence distance perception judgments in *action* space, consistent with prior work [Bruder et al. 2012; Willemsen et al. 2008]. Furthermore, the current study specifically examined the effects of IPD mismatch for users with IPDs smaller than the supported HMD range, which generalizes the findings from the previous studies to an understudied population.

7 CONCLUSION

Across three experiments, we investigated if the mismatch between users' actual IPD and an HMD's IPD affects distance judgments in *action* space. In the first two experiments, we found that IPD mismatch had minimal to no effect on distance judgments in *action* space for users with IPDs below the minimum supported range. This finding was reinforced by the results of Experiment 3, where we considered groups of people whose IPDs were supported or unsupported by the HMD. All three experiments showed that participants underestimated distances, consistent with prior work. Our findings suggest that the IPD mismatch of an HMD is not the main reason people underestimate distances in *action* space.

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SUPPLEMENTARY MATERIALS TO INTER-PUPILLARY DISTANCE MISMATCH DOES NOT AFFECT DISTANCE PERCEPTION IN ACTION SPACE

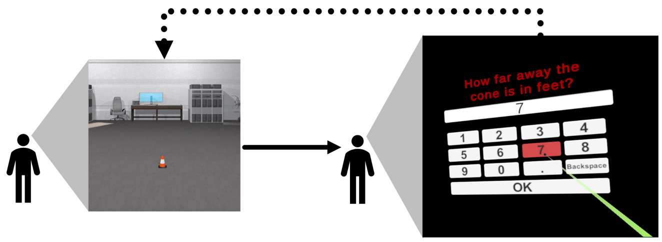

Figure S1: A representation of the verbal estimation task is shown in this figure. At first, a participant judged the distance of the virtual traffic cone, shown in Figure S1(i). After pressing the "Trigger" button of the Vive Pro hand controller, they saw the User Interface with the environment turned off, shown in Figure S1(ii). They interacted with it to record their estimated distance. Once they pressed the "OK" button in the user interface, their data was recorded, and they started a new trial.

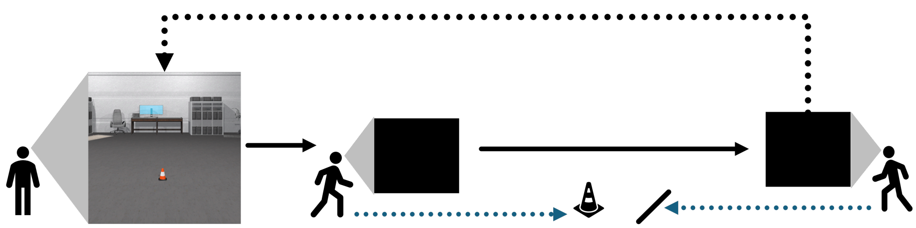

Figure S2: A representation of the blind walking task is shown in this figure. At first, a participant judged the distance of the virtual traffic cone, shown in Figure S2(i). After pressing the "Trigger" button of the Vive Pro hand controller, they started walking towards the traffic cone while the HMD screen remained black, shown in Figure S2(ii). After reaching the estimated location, they recorded their response by pressing the same button on the hand controller and walking back to the starting point with the experimenter's help while the HMD screen remained black, shown in Figure S2(iii). Once they returned to the starting position, they pressed the "Trigger" button again to start the next trial.

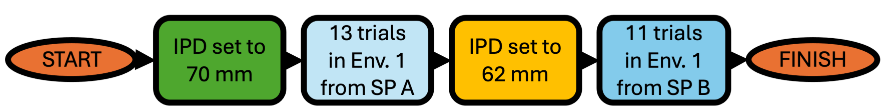

Figure S3: Possible sequence of executing the distance estimation task in Experiment 2 and 3 with blind walking. "SP A" and "SP B" represent the starting points A and B. All participants' actual IPD was measured before running the experiment.