# The influence of body orientation relative to gravity on egocentric distance estimates in immersive virtual environments

by

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## *Author's Declaration*

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

# *Abstract*

Virtual reality head mounted displays (VR-HMD) are a flexible tool that can immerse individuals into a variety of virtual environments and can account for an individuals head orientation within these environments. Additionally, VR-HMD's can allow participants to explore environments while maintaining different body positions (e.g sitting, and laying down). How these discrepancies between real world body position and virtual environment impact the perception of virtual space or, additionally, how a visual upright with incongruent changes in head orientation affects space perception within VR has not been fully defined. In this study we hoped to further understand how changes in orientation (laying supine, laying prone, laying on left side and, being upright) while a steady visual virtual upright (presented in the Oculus Rift DK1) is maintained can effect the perception of distance. We used a new psychophysics perceptual matching based approach with two different probe configurations (L- and T shape) in order to extract distance perception thresholds in the four previously mentioned positions at egocentric distances of 4, 5, and,6 meters. Our results indicate that changes in orientation with respect to gravity impact the perception of distances within a virtual environment when it is maintained at a visual upright. Particularly we found significant differences between perceived distances in the upright condition compared to the prone and laying on left side positions. Addtionally, we found that distance perception results were impacted by differences in probe configuration. Our results add to a body of work looking at how changes in head and body orientation can affect the perception of distance, however, more research is needed in order to fully understand how these changes with respect to gravity are affecting the perception of space within these virtual environments.

## *Acknowledgments*

I would like to thank family and friends for all the love and support. I would also like to thank my supervisor, Dr Michael Barnett-Cowan, for providing invaluable guidance and feedback through these past years. I would also like to thank Dr. Markus Leyrer, and Jackie Rauhut. This thesis would not have been possible without them, or without those from the Department of Kinesiology at the University of Waterloo whom I have learnt so much from over the last years.

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# *Introduction*

## *Overview*

Our ability to orient ourselves or interact with the environment relies on our ability to generate a percept of the visual space. To form a coherent percept of the space and objects around us we must extract sensory information from the environment; this is an essential ability in order to perform our everyday tasks and work. Understanding the way we integrate and combine this extracted sensory information can inform us on the how different sensory modalities contribute to generating our representation of the world and objects around us. For example, when playing catch with a friend some of the things we might need to figure out are how to orient ourselves in relation to our friend, how tall our friend is and how far away they are. These characteristics can be established by extracting information from the environment using our different sensory modalities like vision, proprioception, or our vestibular system.

Target location representations can be formed in either egocentric (relative to the observer), exocentric (relative to another object), or allocentric (relative to a fixed location) reference frames (Sharika, Ramakrishnan, & Murthy, 2014). Determining how far an object is from oneself (i.e. egocentric distance) relies on our ability to extract available visual cues in the environment (Harris & Mander, 2014). The visual system will rely on available monocular and binocular cues to perceive both the relative and absolute distances of an object (Blohm et al., 2008; Harris & Mander, 2014). Relative distance is the distance between a peripherally viewed object in relation to a fixed point or secondary object; the estimation of this distance is not exact (Blohm et al., 2008). Absolute distances, on the other hand, are exact estimates of object distances (between objects [exocentric distances] and between the observer and a foveated object [egocentric distance]). Continuing with the example above; to throw your friend the ball you will use the available visual scene to determine the distance between you and your friend (absolute egocentric distance), additionally, it has been suggested that how you are positioned influences how far you perceive your friend to be.

Changes in head orientation have previously been reported to change the perception of distance. These changes in the perception of distance with change in head orientation however were attributed to changes in visual cue characteristics (e.g visual linear perspective and visual size perception) (Torok et al., 2017). A recent study has suggested that the changes in distance perception with changes in head position relative to gravity depends also on on-line vestibular signals (Torok et al., 2017). This could mean that when you are throwing your friend the ball, if you tilt your head upwards to look up to the sky before throwing, you may change how far you perceive your friend to be.

One way of investigating these changes to distance perception, due to changes in orientation, is to use virtual reality (VR). Using VR it is possible to have a change in orientation while maintaining the visual environment, thereby, probing if changes in distance perception may or may not be attributed to changes in visual cues as opposed to changes in orientation.

The proposed research will use VR to explore the effect of orientation changes on distance perception in a stable virtual environment. Using a psychophysical task to measure perceived distances in VR this study looks to further understand how sensory systems contribute to our perception of egocentric distances. In this thesis I will review how different sensory modalities contribute to distance perception in real and virtual environments, and how we can measure distance perception within these environments.

### *Visual System Contribution to Distance Perception*

The perception of distance of an object relies on the visual system to extract information about the object and its environment. Monocular cues may be used to generate a rough absolute distance estimation of an object (Mon-Williams & Tresilian, 1999; Harris & Mander, 2014). These monocular cues include occlusion, relative size, familiar size, relative height, texture gradients, aerial perspective, and linear perspective, in addition to, cues produced by motion such as motion parallax, and oculomotor cues like accomodation (Wolfe, Kluender, & Levi, 2018). Cues such as occlusion, relative height, and relative size give us information about the relative distance of objects (Wolfe, Kluender, & Levi, 2018). Occlusion is a relative non-metrical depth cue where information about the depth order is provided - relative distance information allows us to know whether an object is closer or farther from another object or fixation point – information about depth magnitude however is not provided. Relative height and relative size on the other hand are relative metrical cues where with the information provided we can specify in relative terms how much further or closer an object is, for example, we may specify that an object is twice as far as another object. If we want to know exact object distances, absolute distance information between the object and observer is preferred (Blohm et al., 2008). Absolute metrical depth cues such as familiar size can give you more information on an objects exact distance in quantifiable terms/distances, however, this relies on having previous knowledge of the object size (Wolfe, Kluender, & Levi, 2018). In addition to familiar size the oculomotor cue accommodation can be used to generate a rough estimate of an objects absolute distance, this cue however has been found to be effective within 2-3 meters with the information provided suffering past these distances (Wolfe, Kluender, & Levi, 2018; Feldstein, 2019). Other cues effective ranges include: 0 - >30 meters for occlusion and relative size, > 30 meters for aerial perspective, 0 – 30 m for motion parallax (Feldstein, 2019).

In addition to monocular cues our visual system will additionally make use of binocular cues such as retinal disparity and vergence. Effective distance ranges for vergence lies within the 0 – 2 meter distances and the effective range for binocular disparity lies within 0 - 30 meters (Feldstein, 2019). All available aforementioned depth cues are then combined in order give us a sense of the space around us. Cues are combined based on their reliability within the environment in addition to their availability within the distance of interest (Pfautz, 2000; Kluender, & Levi, 2018). Within the environment used in this study (see Figures 2 & 3A) described later on in this thesis binocular disparity and linear perspective cues are most relevant and likely the primary cues combined to create and idea of the presented virtual space.

Even with all these cues extracting absolute distance is a hard task for the visual system and while vergence (and vergence angle), and disparity provide possibly more reliable information Blohm and colleagues (2008) argue that they may not be sufficient (Mayhew & Longuet- Higgins, 1982; Mon-Williams & Tresilian, 1999; Mon-Williams, Tresilian & Roberts, 2000; Harris & Mander, 2014; Clement et al., 2020). Blohm and colleagues argue that eye and head orientation information is needed in order to use retinal disparity to extract absolute distance information (Blohm et al., 2008).

In addition to monocular, binocular, and oculomotor cues, perspective cues (like the aforementioned linear perspective and texture gradient cues) and the ground plane reference are available; we can additionally use these to perceive the space around us (Loomis & Knapp, 2003; Wu, Ooi, & He, 2007). The Sequential Surface Integration Process (SSIP) hypothesis, proposed by Wu and colleagues (2007), postulates that the visual system will use the available oculomotor

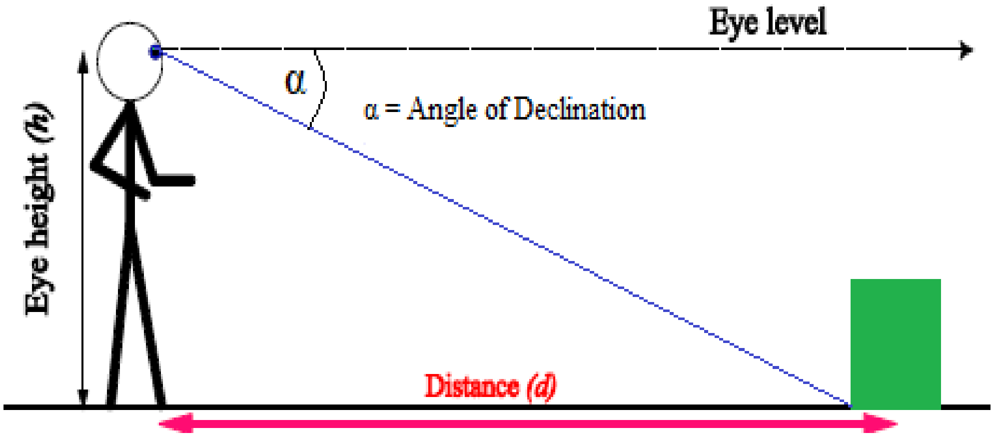

*Figure 1:* ***Angle of Declination***

cues (accommodation, vergence), binocular disparity, and texture gradients (perspective cues) to construct the ground surface so that it may be used as a reference for locating objects in space. In a series of experiments Wu and colleagues (2007) explored the effect of different texture gradients on the ground plane reference by examining changes in perceived eye level (projection line parallel to the ground surface stemming from the eye; determined by body cues [proprioception and vestibular inputs] as well as external visual cues) and the perception of egocentric object distances (Wu, Ooi, & He, 2007; Leyrer, 2014). Since the angle between the perceived eye level and the object projection (see Figure 1: Angle of Declination) can be used to determine the egocentric distance of an object they manipulated the available linear perspective texture gradients cues and measured judged eye level and estimated egocentric distance (Howard, 2012). Experimenters also explored the effect of full lighted vs limited visual cue environments. They found that converging vs parallel linear perspective cues significantly influenced the perceived eye level and object egocentric distance. The parallel-line rule (retinal images of converging lines are represented as parallel) and the horizon rule (the convergence point of converging lines is at the horizon) were assumed by the SSIP affecting judged eye levels that differed from true eye level leading to altered ground plane perception for participants. The results in these series of experiments were in line with the SSIP hypothesis in that the ground surface is constructed from both available near depth visual cues and perspective cues where the visual system will still rely on the above assumptions even in lighted full cue environments; supporting the importance of ground plane reference in distance estimation and object localization.

In addition to linear perspective cues, changes in body position have also been seen to affect judged eye levels and egocentric distances. A series of experiments done by Leyrer (2014) suggested that eye level is determined by body-based cues over visually guided cues in both real and virtual environments. Leyrer (2014) also found that distances were overestimated in a shifted frame of reference study where participants were laying supine on the floor and the virtual environment presented was upright; judged eye levels were additionally affected by this shift and supported their findings that eye levels are determined by body-based cues. These studies in combination support that visual cues and the ground plane reference are important in the perception of distance and may additionally be affected by changes in head orientation.

### ***Vestibular Contribution to Distance perception***

The contribution and role of the vestibular system, through changes in gravity or head and body orientation, on the perception of space and distance is still not yet fully understood. Early hypotheses looking at how different head positions affect distance perception include Thor and Wood's (1966) vestibular hypothesis and the flattened sky dome/heavens interpretation of the moon illusion by Rock and Kaufman (1962) (Zinkus & Mountjoy, 1969; Carter, 1977; Harris & Mander, 2014; Toskovic, 2010). Both hypotheses however focus on the visual distortions or changes to available depth cues as a consequence of a change in head orientation. The vestibular hypothesis (or visual-vestibular interaction hypothesis) proposed that the effect of the vestibular system on visual cues affects distance perception where head tilt or vestibular stimulation results in visual distortions (Zinkus & Mountjoy, 1969). The flattened sky dome model alternatively hypothesises that the moon in the horizon is perceived to be farther and when on the zenith, closer (Harris & Mander, 2014; Toskovic, 2010). This model falls under the apparent distance theory where the unequal distribution of distance cues - when looking up at the sky vs when looking at the ground – leads to misperceived distance in different viewing conditions (Higashiyama & Adachi, 2006; Toskovic, 2010).

Zinkus & Mountjoy (1969) probed the vestibular hypothesis by having seated participants complete a distance matching task. First, a disk was displayed in front the participant then they were either tilted back (facing the ceiling) or rotated 90 degrees to the right – another disk was already displayed in those new positions. Participants were then asked to remember the distance of the front facing disk and match it in their new position with the disk in front of them (Zinkus & Mountjoy, 1969). They found that when there was a change in position relative to gravity (backwards tilt) the participants would move the disk closer; the participants perceived the disk above them to be farther and smaller and so moved the disk closer to them to 'match' the distance (the two disks were already placed at equal distances) (Zinkus & Mountjoy, 1969). Zinkus & Mountjoy (1969) concluded that the results added strength to the vestibular hypothesis where depth perception misestimations were a result of vestibular stimulation disrupting visual processes. Other similar studies looking at head orientation related errors in depth perception often have differences in visual scene (and context) which confound the correlation to head orientation (Harris & Mander, 2014). Therefore, it may be that the visual context within these different head orientations are affecting the perception of distance; this would then more closely follow the flattened heavens interpretation of the moon illusion (Harris & Mander, 2014).

To look at the importance of visual context within in different head/body orientations Harris and Mander (2014) used the York Tumbling and Tumbled Room; here they could manipulate a participant's actual orientation relative to gravity as well as their perceived orientation. When participants were in the York Tumbled Room they were either standing upright with the room upright or laying supine while the room matched the orientation (both the room and participant were tilted resulting in coherent visual context). When the participants were in the York Tumbling Room 4 different room/participant orientation combinations were used: 1) both upright, 2) both tilted (90 degrees toward the ceiling), 3) room upright and participant tilted (90 degrees toward the ceiling), and 4) room tilted (90 degrees toward the ground) and participant upright (Harris & Mander, 2014). The results showed that the distance of the experimental object was perceived to be closer when the participant was tilted or perceived to be tilted (supine) (Harris & Mander, 2014). The results here are compatible with the flattened heavens interpretation of the moon illusion where objects are perceived to be closer when lying supine; the importance of visual context is also highlighted in these results where the distance perception effects were also seen when the visual context was titled and not the person (Harris & Mander, 2014). Similar to these results Scotto di Cesare and Colleagues (2014) looked at the effect of visual scene tilt and actual body tilt (changes in pitch) on distance perception by using a pointing task. They found that forward visual scene tilts resulted in overshoots and backward visual scene tilts resulted in undershoots (Scotto di Cesare et al., 2014). This was, however, also contrasted with results showing that a forward body tilt with the scene kept parallel to the participants resulted in undershoots – opposite to results from the visual scene tilt (Scotto di Cesare et al., 2014). These results along with that of Zinkus & Mountjoy (1969), as well as other similar studies, seem to show a pattern opposite to that of Harris & Mander (2014); backward head tilts or lying supine resulted in distances being perceived to be farther and, conversely, with a forward head tilts or when lying prone distances are perceived to be closer (Toskovic, 2010; Harris & Mander, 2014; Scotto di Cesare et al., 2014).

Effort based theories like that described by Bishop Berkeley (1732), embodied cognition movement (Van der Hoort et al., 2011), and the gravity theory predict the elongation of distances when lying supine (Harris & Mander, 2014; Torok et al., 2017; Clement et al., 2020). Bishop Berkeley (1732) described an effect of imagining the effort of walking or taking action along a distance – uphill distances would seemingly require more effort resulting in the distance being perceived as longer (Harris & Mander, 2014). Similar to this Van der Hoort and Colleagues (2011) describe the idea of the embodied cognition movement which falls within Gibson's ecological approach where the physical properties of a person can define the affordances towards an object. The embodied cognition movement more specifically argues that the effort needed to interact with an object influences visual perception – an upward slope of a hill, when participants are carrying a heavy backpack, or the size of the person all affect the perceived distance of an object (Van der Hoort et al,. 2011; Clement et al., 2020). Finally, the gravity theory (focusing more on vertical distances) is in agreement with the ideas above where a vertical distance is judged to be longer when viewed from below due to the perceived higher amount of energy needed to be expended to act on that distance compared to a distance below viewed from above (Clement et al., 2020). All three theories predict that the imagined effort to reach or act towards an object can change how far away we perceived that object to be – distances above us are perceived to be farther away and distances below us are perceived to be closer.

A few studies have been done that support the prediction of the effort-based theories (Scotto di Cesare et al., 2014; Torok et al., 2017, Clement et al., 2020). The study by Torok and Colleagues

(2017) supports the prediction of the gravity theory, however, they also add to the literature demonstrating a possibly more direct effect of vestibular stimulation on distance perception as opposed to the effect of an internal representation of the imagined effort needed to take action towards an object. Torok and colleagues (2017) used a CAVE system to present the visual environment, they asked participants to judge the distance of an object presented at different elevation levels – one on the horizon, and one above and below the horizon – the head tilt angle matched the object elevation angle. During each judgement they also used galvanic vestibular stimulation (GVS) to stimulate the vestibular organs and enhance the natural vestibular responses and simulate the sensation of roll tilt (Torok et al., 2017). Torok and colleagues (2017) found that participants perceived distances to be longer when their head was tilted upward and shorter when their head was tilted downward; they also found that the event-related GVS increased these perception biases strongly (Torok et al., 2017). Torok and colleagues (2017) argue that although this supports what was predicted by the gravity theory it also shows that the effect of position relative to gravity on distance perception may not be solely due to visual context and association, but, perhaps due to online vestibular system control suggesting a multisensory integration mechanism. Additional studies done in micro- and hyper-gravity, as well as through the manipulation of participant orientation, support the idea that the vestibular system plays a more direct role in the perception of distance (Higashiyama & Adachi, 2006; Toskovic, 2010; Clement et al., 2013; Harris & Mander, 2014; Clement et al., 2016; Torok et al., 2017, Clement et al., 2020). In order to further expand on this work and investigate the effect of vestibular stimulation on distance perception, without changes in visual context, virtual reality could be used.

### ***Virtual Reality and Distance Perception***

Virtual reality can be used to probe how we perceive distances particularly in head-mounted display VR (HMD-VR) where environments can be completely manipulated and what the participants see can be controlled. Previous studies probing the perception of distances, however, have consistently found evidence of misestimation, particularly underestimation, of egocentric distance perception when perceiving distances in virtual reality environments. Loomis & Knapp (2003) and Naceri and colleagues (2010) outline some of the proposed issues and hypothesis in VR and the misestimation of distance. These include Field-of Vision (FOV) reduction with head-mounted displays (HMD), physical properties of the HMD (e.g weight), photo/graphical realism of the display and difference between real and virtual environment, and the form of measurement (Loomis & Knapp, 2003; Thompson et al., 2004; Naceri et al., 2010; Grechkin et al., 2010; Kelly et al., 2017; Buck et al., 2018; Hornsey et al., 2020).

Loomis & Knapp (2004) studied the effect of limited HMD FOV in real environments on the perception of distance. Using a HMD like apparatus to simulate limited FOV they found no underestimation of egocentric distance compared to when participants did not have simulated HMD limited FOV. Grechkin and Colleagues (2010) similarly concluded no changes with distance perception with HMD limited FOV in real environments. Additionally, work looking at the weight of the head mounted display has concluded that the differences seen in distance perception do not significantly result from these technical factors (Grechkin et al., 2010; Kelly et al., 2017).

Grechkin and Colleagues (2010) additionally tested the proposal that graphic/photo realism of an environment as a possible explanation for the underestimations of perceived distance. They used large screen immersive displays and compared a virtual simulation and photo of the same environment; they found no significant effect on distance – similar to results by Thompson et al., (2004) and Messing & Durgin (2005) who used an HMD to test this hypothesis.

Underestimation of distances in VR has also been found regardless of the measurement form/task (Loomis & Knapp, 2003). Loomis & Knapp (2003) summarized two experiments where 3 measurement forms/tasks for distance perception in HMDs were studied - experiment 1: verbal report, visually directed walking, and judgement of passability of an aperture; experiment 2: verbal report, triangulation by walking, and size judgement task – all of which, regardless of task, resulted in underestimations of distance within the virtual environment. Task differences in distance perception studies have been found outside of VR where distance estimations differ during verbal report and distance matching tasks (Higashiyama & Adachi, 2006; Toskovic, 2010). Toskovic (2010) argues that to transform perception into a verbal report additional higher cognitive processes are required; this means previous experiences can be used and interfere with the perception of the distance; he argues that perceptual matching tasks instead are a more direct measure of pure perceptual processes.

Although the reason for misestimation of perceived distances in VR is still unknown it remains a valuable tool that allows the participant to be positioned in a variety of orientations while keeping the visual scene (and context) parallel to the participant. Aside from a few studies – including that of Harris & Mander (2014) – there has not been a great deal of probing into the role of vestibular stimulation through body orientation changes on perceived distance while controlling for visual scene and context (Harris & Mander, 2014). Additionally, by using a perceptual matching task we can more directly probe the perception of distance without the potential interference of higher cognitive processes; using a matching task may also allow a further look into possible task effects on distance perception in VR.

### *Psychophysical Perceptual Matching Tasks to Study Distance Estimation*

Psychophysics based perceptual matching tasks may help remove some of the ambiguity in regard to task differences found in distance perception literature due to their robust ability to tease out the perceptual thresholds. Additionally, these psychophysics task do not involve any action or movements; the tasks are purely perceptual. In this study a T and L configuration psychophysics perceptual matching task was used. In previous literature the L configuration was used by Li, Phillips &, Durgin (2011). They adapted the extent matching task (Exocentric L task) normally used to measure exocentric extent distance perception and developed an Egocentric L task that can measure egocentric distance perception using exocentric extents (see Figure 2) (Li et al., 2011). In their study they measured the matching distances using meters, here we adapted the task using the method of constant stimuli to find participant perceptual thresholds of the perceived distance. By using the method of constant stimuli we can generate a psychometric function and extract a participants absolute threshold. The absolute threshold in this case would represent the distance at which the participant perceived both distances to be equal – the participant responded that the reference distance was greater than or lesser than the egocentric distance in 50% of the responses. This absolute threshold is reffered to as the Point of Subjective Equality (PSE) which in this case would also represent the perceved distance of the participant. In addition to the PSE using the method of constant stimuli and generating a psychometric function allows us to extract the Just Noticeable Difference (JND) which gives us a measure of the precision of the responses. Similarly, the T configuration perceptual matching task (where the two frontal extents are moved to match the egocentric distance between the frontal extents and the participant) used by Leyer (2014) was adapted so that the method of constant stimuli could also be used to find participant perceptual thresholds of the perceived distance (see Figure 3). In Leyer (2014) they found distances to be overestimated in VR when using the T configuration task. They attribute this result to the T configuration task where previous literature has found that exocentric distance estimation tends to be overestimated, this is unlike literature using the L configuration task which has found underestimation of egocentric distances in VR. By using these two psychophysics based perceptual matching tasks we can further tease out the effect of orientation changes where regardless of task differences the effect, if any is present, of orientation should persist. Using both tasks in combination with HMD-VR we hope to expand our understanding of the potentially direct effects of vestibular contribution on the perceptual process of distance perception.

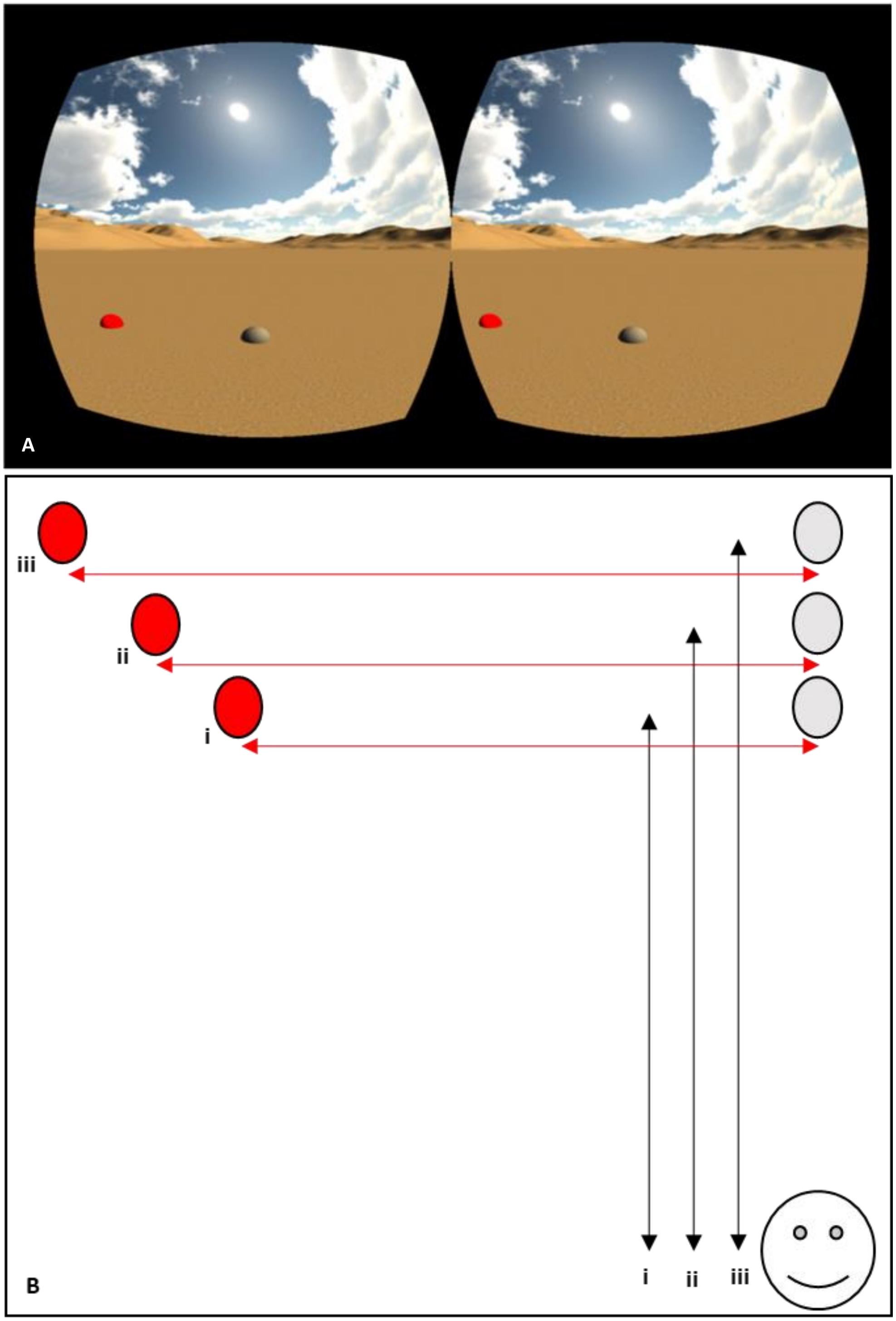

*Figure 2:* ***Virtual Environment and L Configuration Task Schematic**. **A)** L Configuration task at 4 meters within the presented virtual environment **B)** All 3 egocentric distances for the L configuration task – i) 4 meters, ii) 5 meters, iii) 6 meters – the distances represented by the red arrows change to the appropriate intervals tested for that distance (see Table 1), distances represented by the black arrows (egocentric distances) do not change.*

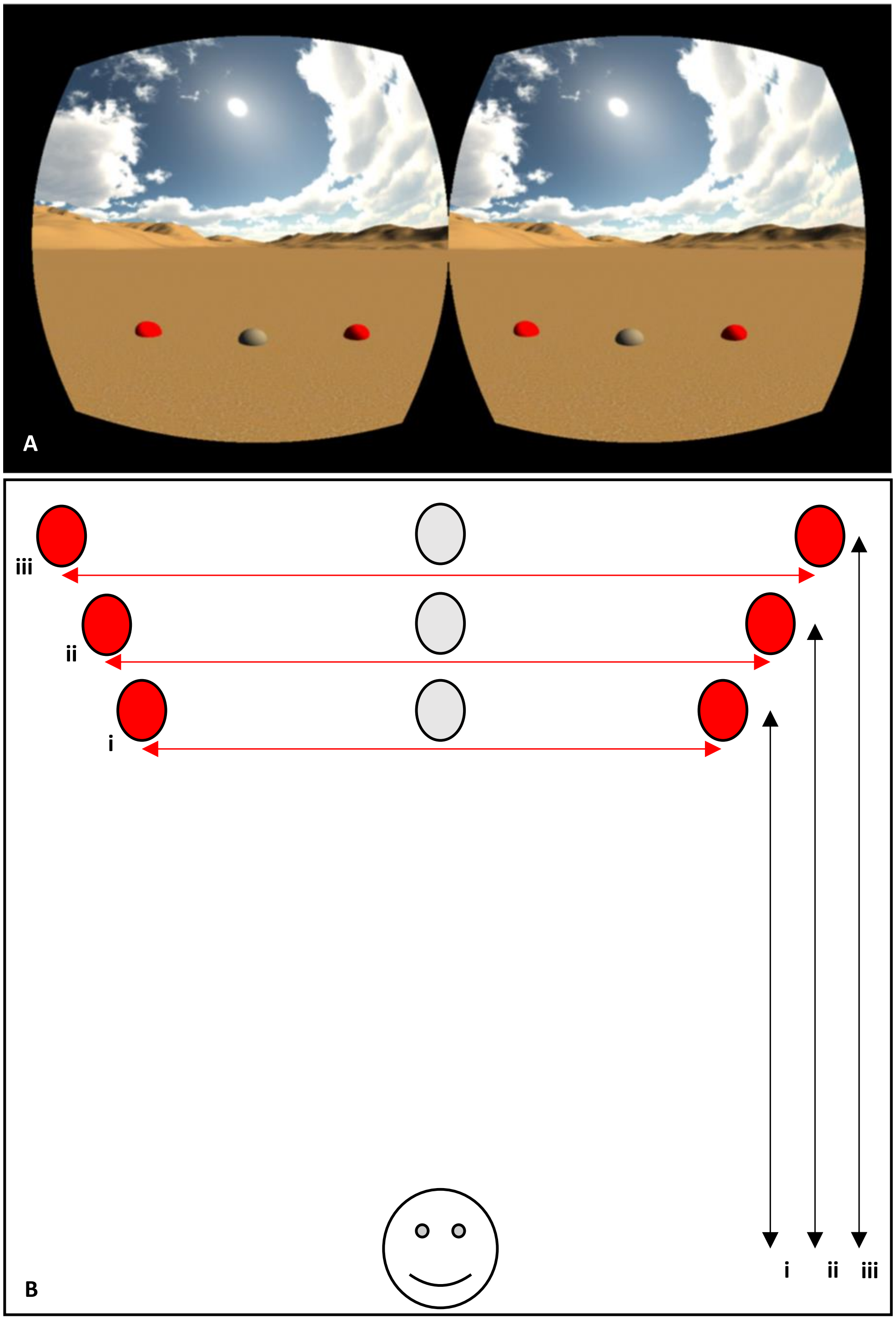

*Figure 3:* ***Virtual Environment and T Configuration Task Schematic****.* ***A)*** *T Configuration task at 4 meters within the presented virtual environment* ***B)*** *All 3 egocentric distances for the T configuration task – i) 4 meters, ii) 5 meters, iii) 6 meters – the distances represented by the red arrows change to the appropriate intervals tested for that distance (see Table 1), distances represented by the black arrows (egocentric distances) do not change.*

### *Purpose & Hypotheses*

Currently, we know that vestibular stimulation through changes in orientation has an effect on the perception of distance, however, it is still unclear whether this effect is a result of changes to visual context caused by changes in orientation, or more direct vestibular control. In accordance with this our primary purpose is to determine if there is an effect of body position changes on distance perception within VR when the visual context is kept the same throughout each body position. We hypothesize that the changes in body orientation will have an effect on the perception of distance while maintaining a relative visual upright in VR.

Our secondary purpose was to explore if the perceptual distance estimation errors are task dependent within VR when using more robust psychophysical perceptual matching tasks. We hypothesize that within VR the distance estimation errors will be task dependent.

## *Methods*

### *Participants*

Thirty-six right-handed adults were recruited from the University of Waterloo, Canada. All participants self reported normal or corrected to normal visual acuity and stereo acuity. Participants were either financially compensated for their participation or received course credit. Of the 36 participants twenty-two participants (11 women; mean age 21.14 ± 4.2) remained after data processing and analysis (see Data Analysis).

### *Ethics Statement*

In this experiment, participants started by completing a written consent form. All experiments were performed in accordance with the 1964 Declaration of Helsinki and were approved by the ethical committee of the University of Waterloo, Canada. All participants were debriefed and informed of the purpose of the study at the end of the experiments.

### *Stimuli and apparatus*

The experiment was developed with Unity 3D 4.3. We displayed a virtual environment, consisting of a textured flat ground plane, distant hills and a sunny sky with clouds (no other familiar size cues) through an Oculus Rift (Development Kit 1) with a resolution of 640 × 800 pixels per eye (in stereo) (see Figure 11). For orientation tracking of the head, the orientation sensor of the Rift was used. The head position was set individually for each participant and not tracked in real time. For indicating the egocentric distance in the perceptual-matching task we used a dark-grey hemisphere. To indicate the (exocentric) matching intervals we used one (in the L - configurations) or two (in the T - configurations) red hemispheres (see Figures 2 & 3). All displayed hemispheres had a virtual width of 50 cm. The participants used a gamepad (Play Station 3 Controller) and two different buttons to decide whether the shown exocentric interval was larger or smaller than the depicted egocentric interval. For the positioning of the participants in all body orientations except the standing orientation a massage table was used, this enabled the participants to stay comfortable across the different body orientations during the experiment.

### *Design and Procedure*

All participants received written and verbal instructions for the experiment and the corresponding psychophysics task. A within-participant design was used, and all participants were randomly assigned to an order (counterbalanced) in which the conditions were presented. All participants experienced the virtual environment in four different body orientations: (1) standing upright, (2) laying supine, (3) lying on their left side or, (4) lying prone. The visual environment displayed in the HMD was aligned with the body axis in all four conditions.

At the beginning of the experiment participants donned the HMD, with assistance from the experimenter, and were handed the gamepad. Participant used two buttons to indicate whether the exocentric distance between red targets (T - configuration), or between red and grey target (L - configuration) was larger or smaller than the egocentric distance between the participant and the grey target (see Figures 2 & 3). For both target configurations (T- or L - configuration) the psychophysical method of constant stimuli approach was used. Three egocentric distances (4, 5, and 6 meters) were presented. For each target distance participants had to complete eleven trials where exocentric distance intervals varied in 25-centimeter steps (i.e. 2.75:0.25:5.25, 3.75:0.25:6.25 and, 4.75:0.25:7.25 for 4, 5, and 6 meter egocentric distances respectively). All participants completed 11 trials at each distance (x3) in each body orientation (x4) for both target configurations, resulting in 264 trials total for the experiment. After completing the experiment participants took off the HMD with assistance from the experimenter and were subsequently debriefed.

## Analysis

### Data Analysis

To determine participants point of subjective equality (PSE) and the just noticeable difference (JND) a cumulative logistic psychometric function $\left(y = \frac{a}{1+e^{-\left(\frac{x-x_o}{b}\right)}}\right)$ was fit to participant responses for each condition. The PSE and JND were split according to body position and task resulting in 8 PSE's and JND's, for each of the 3 distances, for each participant. At this stage eight participants were excluded from the analysis due to participants not following experimental procedures, missing data files, or data that could not be reliably fit to the psychometric curve ($R^2 < 0.2$). Further preprocessing was completed on the data from 27 participants (16 women; mean age 21.3 ± 4.1 (SD) yrs, range 18-36). The data was then tested for normality and outliers were removed. Outliers were detected using the Inter-Quartile Ranges (IQR) where values above Quartile 3 + 3xIQR and values below Quartile 1 – 3xIQR were removed. Participants who had these outlier data points were completely removed from further analysis in order to run the subsequent repeated measure ANOVA without missing data points. Additionally, the data for the PSE and JND was found to be not normal. The bestNormalize function in R - of which multiple transformations are performed and the best one is picked based on the goodness of fit - was used to normalize the data. A log transform was used to normalize PSE data and the Yeo-Johnson transformation of the boxcox family of transformations was used to normalize the JND data for further analysis. At this stage of the 36 participants 22 (11 women; mean age 21.14 ± 4.2) were used in the subsequent statistical analysis.

### ***Statistical Analysis***

In order to look at the effect of body position and task on perceived distance at all three distances a 3 (Distance: 4/5/6 meters) x 2 (Task: T/L) x 4 (Body Position: upright/supine/prone/left side) repeated measures ANOVA (RMANOVA) was done. Additionally, a 3 (Distance: 4/5/6 meters) x 2 (Task: T/L) x 4 (Body Position: upright/supine/prone/left side) repeated measures ANOVA was done using JND values to determine differences in the precision of responses among the different conditions. Of particular interest, as per our main hypothesis, we wanted to explore the effect of body orientation on distance perception.

To further explore task differences a paired t-test was done on the cumulative mean perceived distances in the upright body position between the L and T configuration tasks. Additionally, 2 one sample t-tests comparing the cumulative mean of the T task in upright posture to the verdical distance value, and the cumulative mean of the L task in the upright posture to the verdical distance value. These were done to determine differences between perceived distances in the respective task and the actual distances measured.

All significant main effects or interactions were followed up by appropriate pairwise comparisons and all results were reported with an alpha level of 0.05. All data was analyzed using R version 3.6.1.

## *Results*

The average PSE's, averaged across participants, for each distance, task, and body position are shown in Figure 4. Additionally, the average JND's for each distance, task and body position are shown in Figure 5.

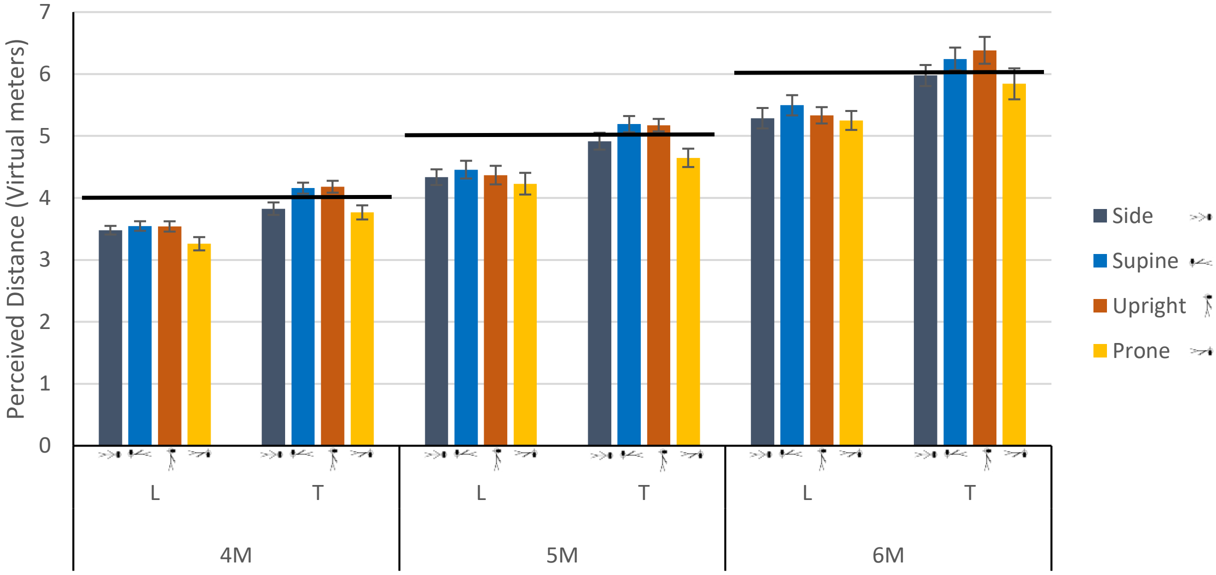

*Figure 4:* ***Average Perceived Distance for Each Orientation, at Each Task, for all Distances****.* *PSE's presented in virtual meters, data was transformed to normal for data analysis using the log transform – log values not presented here.*

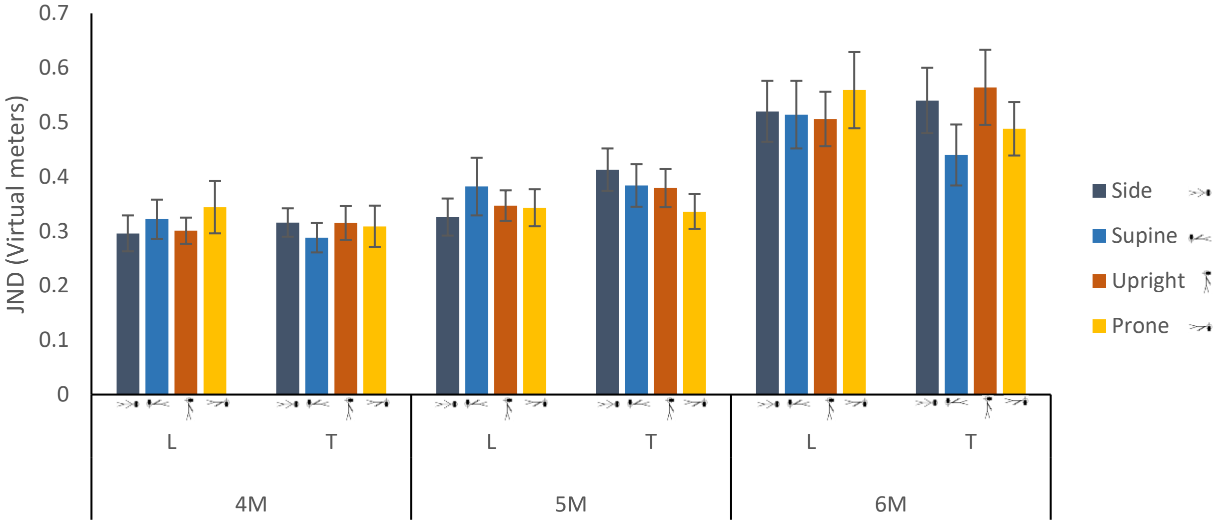

*Figure 5:* ***Average JND's for Each Orientation, at Each Task, for all Distances.*** *JND's presented in virtual meters, data was transformed to normal for data analysis using the Yeo-Johnson transform – transformed values are not presented here.*

A 3 x 2 x 4 within groups RMANOVA revealed a significant main effect of distance [F(2,42) = 691.13, p = 3.47e-21, $\eta_p^2 = 0.633$], task [F(1,21) = 30.95, p = 1.60e-05, $\eta_p^2 = 0.197$] (see Figure 7), and body position [F(3,63) = 7.71, p = 5.74e-04, $\eta_p^2 = 0.057$] (see Figure 6) for the PSE values. Pairwise comparisons of body position show that perceived distances were significantly different in the prone and left side laying positions compared to standing upright (p = 1.6e-08 and p = 2.7e-04, respectively), there was no significant difference between the standing (LogPSE mean = 0.673, SE = 0.009 & PSE mean = 4.83, SE = 0.097) and supine (LogPSE mean = 0.675, SE = 0.009 & PSE mean = 4.85, SE = 0.095) positions (p = 1). Additionally, 2-tailed pairwise comparisons showed a significant difference between laying on the left side and laying prone compared to laying supine (p = 1.3e-03 and p = 1.1e-07, respectively), as well as, in the prone position compared to the laying on the left side position (p = 0.038) (see Figure 6). There was no significant three-way interaction between distance, task, and body position [F(6,126) =

1.14, p = 0.34, $\eta_p^2 = 0.0029$], and no significant two-way interactions between distance and body position [F(6,126) = 1.44, p = 0.234, $\eta_p^2 = 0.0028$], distance and task [F(2,42) = 0.134, p = 0.827, $\eta_p^2 = 0.000099$], and task and body position [F(3,63) = 1.92, p = 0.151, $\eta_p^2 = 0.0086$]. Figure 8 also linearly represent the upright data for both the T and L configurations. This visualization more clearly depicts the differences between the tasks while in an upright posture. A paired t-test between the upright L task and upright T task PSE's revealed a significant difference between the two conditions (t = 10.22, df = 65, p = 3.7e-15). Additionally, 2 one sample t-tests comparing the T task and L task in the upright position to the verdical distance mean found a significant result comparing the L task in the upright position (t = -6.16, df = 21, p = 4.09e-06) but no significant difference comparing the T task in the upright position (t = 0.96, df = 21, p = 0.35).

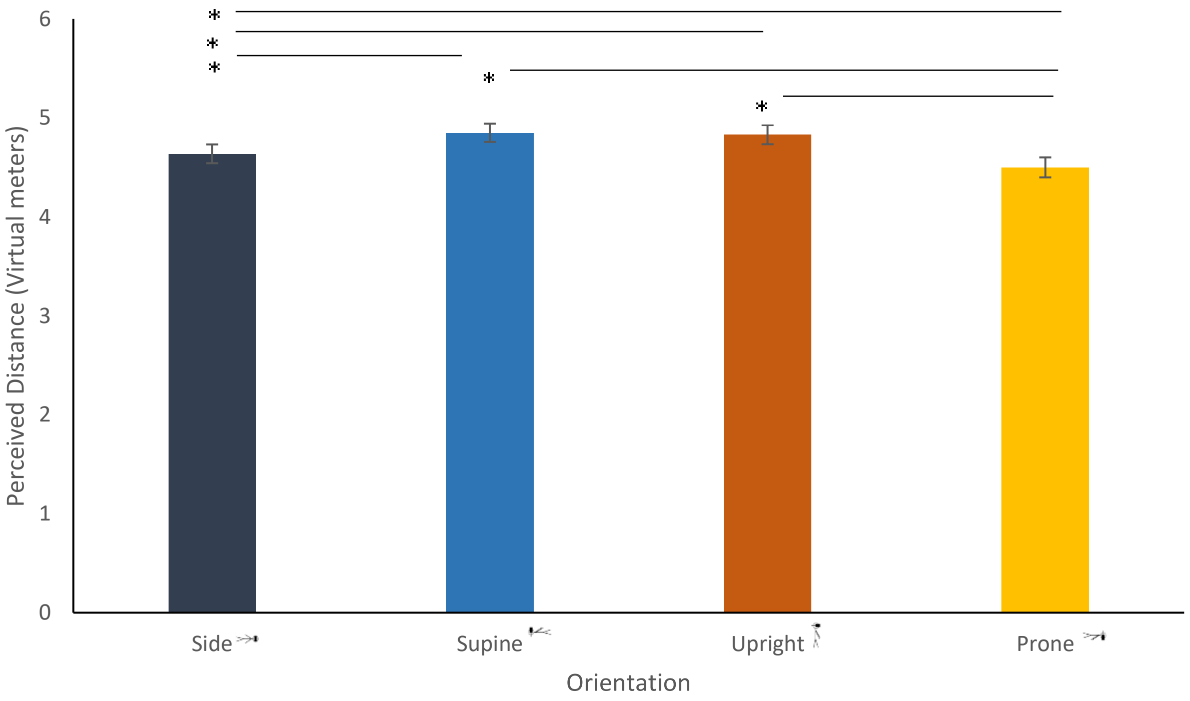

*Figure 6: **Average Perceived Distance for Each Orientation**. Data was transformed to normal for data analysis using the log transform – log values not presented here. * Demonstrates significant findings between orientations.*

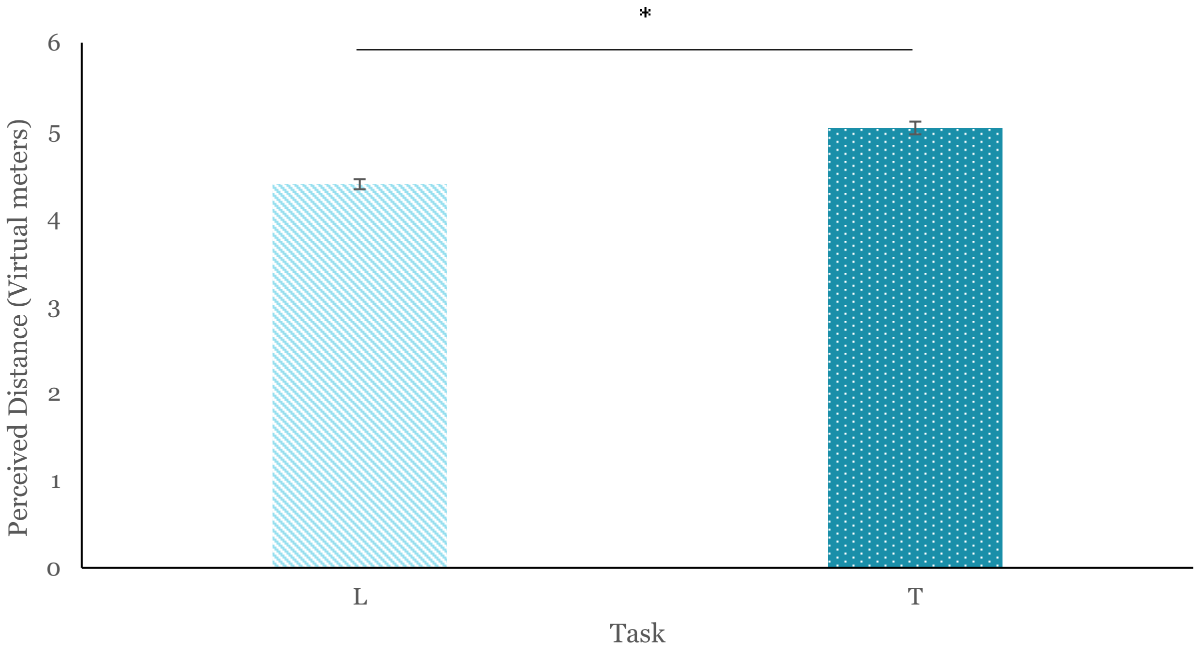

*Figure 7:* ***Average Perceived Distance for Each Task***. *Data was transformed to normal for data analysis using the log transform – log values not present here. * Demonstrates significant findings.*

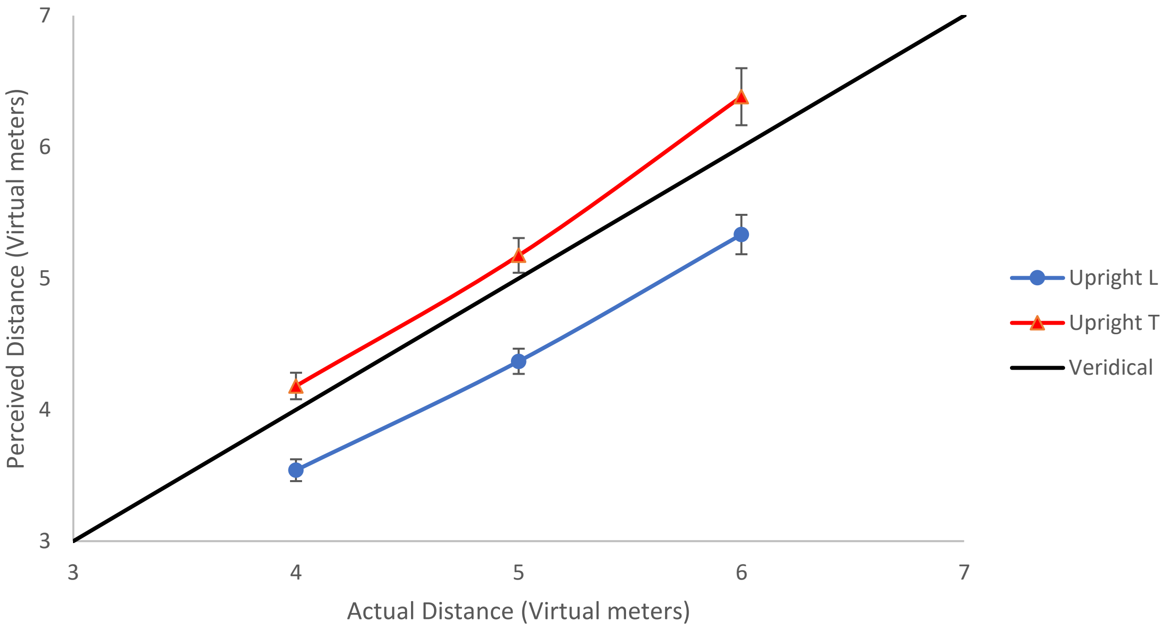

*Figure 8:* ***Perceived Distance in the Upright L and T Configuration Tasks at 4, 5 and, 6 Meters.*** *Upright L configuration (Blue circles) and Upright T configuration (Red triangles) compared to the veridical distances used during the experiment (4, 5, and 6 meters).*

A 3 x 2 x 4 within groups RMANOVA revealed a significant main effect of distance for the JND values[F(2,42) = 52.14, p < .001, $\eta_p^2 = 0.1417$ ]. A one-tailed pairwise comparison showed a significant difference between the 4m distance compared to the 5m and 6m distance (p = 3.1e-05 and p < 2e-16, respectively), and between the 5m distance and the 6m distance (p = 3.9e-14), demonstrating that as the distance increased the JND also significantly increased. There was no significant main effect of task [F(1,21) = 0.03, p = 0.86, $\eta_p^2 = 0.0001$], and body position [F(3,63) = 0.316, p = 0.814, $\eta_p^2 = 0.0019$]. There was also no significant three-way interaction between distance, task, and body position [F(6,126) = 0.253, p = 0.96, $\eta_p^2 = 0.00127$]. Additionally there was no significant two-way interaction effect between distance and task [F(2,42) = 2.07, p = 0.138, $\eta_p^2 = 0.00387$], task and body position [F(3,63) = 0.993, p = 0.402, $\eta_p^2 = 0.00612$], or distance and body position [F(6,126) = 0.869, p = 0.519, $\eta_p^2 = 0.00498$].

## *Discussion*

In order to interact with our environment we use available sensory information to generate a percept of the space around us. Acting on or using the objects around us requires some understanding of various characteristics about that object such as its distance from oneself. The perception of egocentric distance requires the use of our sensory systems to extract information from the environment. The sensory systems involved in this perception, as well as, how they are involved and may interact with one another is still being explored. The visual system and it cues as well as the perception of the ground surface have been found to be important in the perception of distance, however, some evidence is demonstrating that changes in head orientation can affect these cues leading to distance perception distortions. It is still however unknown if the head orientation changes influence distance perception directly or if they are causing distortions in the visual input leading to the disruption of accurate distance perception. This study aimed to assess the effect of changes in orientation on egocentric distance perception in VR using robust psychometric tasks. In so doing we hoped to explore how different sensory systems may contribute to the perception of egocentric distance within virtual environments and whether the effect of head orientation changes on distance perception occur with the presentation of a stable visual environment.

### *Body Orientation and Distance Perception*

Our results show that being in different orientations while maintaining a relative visual upright affected the perception of distance (see Figure 6). The participants perceived distances differed when in the prone and laying on left side positions as compared to the standing upright position. Participants also perceived distances differently when in the prone and laying on left side positions as compared to the supine position, and in the prone position compared to the laying in left side position. This suggests that disruptions in the perception of distance may directly be attributed to a change in head orientation as opposed to these orientation changes disrupting visual scene cues and as a result distance perception. No significant distance perception differences were found when participants were laying supine as compared to when they were standing upright.

In accordance with our primary hypothesis changes in body position influenced the perception of distance when the relative visual upright was maintained. This was true for when participants were lying prone compared to when they were upright. These results follow previous studies where differences in the estimation of egocentric distances were found when participants were tilted forward towards the ground compared to when they were upright (Scotto Di Cesare et al., 2014; Torok, et al., 2017). Scotto Di Cesare and colleagues (2014) examined how a forward body tilt when the visual scene remained parallel to the body affected distance perception during a pointing task. They found underestimation of object distances compared to the upright/non-tilted condition. Torok and colleagues (2017) also found differences in distance perception when the participant was tilted forward compared to being upright however the visual scene was not maintained parallel to the participant as in our study and that of Scotto Di Cesare and colleagues (2014). Interestingly, however, Torok and Colleagues (2017) used GVS while the participant completed the distance estimation tasks and they found that the GVS increased the misestimation biases found in the tilt sham GSV trials, when there was no tilt GSV had no effect on distance perception.  These studies, along with our results, support the idea that changes in head and body orientation may directly affect the perception of distance and that this effect may not only be attributed to changes in the visual scene because of the changing head and body orientations.

Additionally, however, contrary to our primary hypothesis we found no effect on distance perception when laying supine compared to when upright. This result does not align with previous findings where distance perception differences were found when participants are lying supine, or the head is tilted back when compared to standing upright (Zinkus & Mountjoy, 1969; Harris & Mander, 2014; Torok, et al., 2017). Harris and Mander (2014) ran a study in the York Tumbling and York Tumbled room where participants were placed in a supine position or where the room was tilted in a way that visually made it seem as if they were in supine position. Participants would then match the size of a rod held in their hand to one shown in front of them – the perceived distance was then calculated using the length = 2dtan(theta/2) equation where d is distance and theta is the retinal image angle (Harris & Mander, 2014). Harris and Mander (2014) found that when participants were supine, as compared to when the room and the participant were upright, there were differences in the perceived distance of the rod; this was true for when just the participant was supine, when just the room was tilted, and when both the room and the participant were tilted (parallel visual scene) to a supine position. Similarly, Torok and colleagues (2017) found that tilting the head backward resulted in a misestimation of distance whose bias was then increased by the use of GVS. These studies show evidence that lying supine can affect the perception of distance compared to when being upright. Our null result contradicts these studies; however, we found a significant effect on distance perception when lying supine compared to when lying prone. This indicates that there is an effect on distance perception between these two positions, however, any effect between laying supine and standing upright may not be clearly defined in this study.

To our knowledge no previous study has looked at the effect of laying on one's side on the perception of distance. The results in this study demonstrate that laying on your left side affects your perception of distance differently than standing upright, laying prone or laying supine does. Due to the stable visual environment and conditions across the orientations we can attribute these distance perception differences to changes in position. These results should be further probed in future studies as most distance perception studies have focused on changes in orientation relative to gravity in the sagittal plane (tilt) but not in the frontal plane (roll). With the recent increase in the popularity and interest in space travel, both commercial and non-commercial, as well as the commercial use of VR-HMDs it will be important to understand how different orientations and changes in gravity affect our perception of objects and space and potentially our ability to interact with objects in this space.

### ***Task and Distance Perception***

The secondary aim of this study was to look at distance perception during different tasks within VR. Our results support our hypothesis where distance perception was affected differently when comparing the T configuration and L configuration tasks. Linear comparisons (Figure 8) further demonstrate some of the differences between the tasks. Figure 8 shows that perception for egocentric distances in the L configuration tend to be underestimated compared to the actual presented distances, whereas, egocentric distances stay closer to verdical in the T configuration. The L configuration results match results from previous studies where underestimation of perceived distances is common across various different tasks in VR and the real world – it is important to note however that perception of distances is more accurate in the real world and underestimations are commonly found in across most VR studies (Loomis & Knapp, 2003; Knapp & Loomis, 2004; Armbruster et al., 2008; Jones et al., 2008; Grechkin et al., 2010). Toskovic (2010) also describes real world differences in perception of distance dependent on task. They and Higashiyama & Adachi (2006) ran the same protocol (with regards to distance and body orientations) however, Toskovic (2010) ran a perceptual matching task and Higashiyama & Adachi (2006) ran a verbal report task. These studies found opposing directionality of distance perceptions; Toskovic (2010) attributes the differences to the verbal judgement task requiring higher order cognitive resources whereas perceptual matching tasks rely more on direct perception. Additionally, when comparing verbal response methods to motor task such as triangulated or direct blind walking, in the real world, verbal estimates are found to result in distance underestimations (Feldstein et al., 2020). By using these two psychophysical perceptual matching tasks we attempted to avoid any confounds resulting from tasks requiring higher cognitive resources. Additionally, we avoided the use of motor tasks in order to be able to assess changes in orientation.

Unlike many VR distance perception studies Leyer (2014) found overestimation of distances when they used the T configuration task. Previously, overestimation of distances was primarily seen in real world exocentric distance estimation literature; this is where the T configuration has been primarily used to test distances (Leyer, 2014; Peillard et al., 2019). Additionally, studies show that in the sagittal plane exocentric distances seem to be underestimated as opposed to frontal extents where the distances tend to be overestimated (Peillard et al., 2019). Interestingly, Geuss and colleagues (2012) tested exocentric distance perception in VR and found that distances in the sagittal plane were underestimated as in the real world but that distances in the frontal plane were accurate and not overestimated as in the real world. Kelly and colleagues (2015) proposed that the findings by Geuss and colleagues (2012) can be explained with the underestimation being due to the virtual environment (VE) and the accurate estimations being due to a combination of the VE and the normally overestimated frontal extents. In their own experiment Kelly and colleagues (2015) replicated the results from Guess and colleagues (2012) in the same VE, however, when they used a simpler VE (single textured plane) both sagittal and frontal extent distances were underestimated – although the frontal extents were underestimated less than the sagittal extents.

In this study we compared the T and L configuration tasks which to our knowledge had not previously been compared in the literature. An advantage of looking at both tasks is that, with our main objective being body orientation effects, any effect present in one task should be present in the other task. When looking at Figure 4 and Figure 9 in the appendix we see that the pattern of perceived distance for the different orientations in comparison to one another continues throughout both tasks and distances. It is also clear in both these figures and Figure 7 & 8 that there is a task difference where the L configuration is underestimated and the T configuration is not significantly different from the verdical. A difference in the tasks that may account for these varying results is that the position of the red sphere in the L configuration task is farther in the periphery than the red spheres in the T configuration task. For example when both the egocentric and exocentric distances are 4 meters: the visual angle between the reference grey sphere and the red probe sphere differs for each task where the visual angle (VA) in the T configuration task is 26.6º compared to 45º for the L configuration task. The smallest VA in the T configuration task was 19º and for the L configuration task it was 34.5º - these VA are from the trial where there was a 4 meter egocentric distance and 2.75 meter exocentric extent distance. The largest VA in the T configuration task was 33.3º compared to 52.7º for the L configuration task – these are from the trial where egocentric distances were 4 meters and the exocentric extents were 5.25 meters apart (see Table 1 in Appendix for all VAs). We see here that the VA for the T configuration task is half or just less than half of the VA in the L task – this means for the L configuration task the red sphere was farther in the periphery than in the T task. Outside of the fovea spatial acuity drops with increasing peripheral eccentricity; high-acuity is limited to the foveal region this means that presumably the farther the red probe is from the reference grey sphere the more difficult the task becomes (Thompson et al., 2011; Wolfe, Kluender, & Levi, 2018). It is possible that due to the higher VA's seen in the L configuration task it was more difficult for participants to judge distances as compared to the T configuration task. This may explain the task differences seen here in this study however this may not be extrapolated to explain underestimations previously seen within the VR literature when using task dissimilar to the one use here e.g verbal report or direct blind walking. Future studies need to try and tease apart why this T configuration task differs from other tasks that consistently result in underestimations in VR.

Finally, JND results show that there is a significant difference in JND between the different distances. A one tailed pairwise comparison t-test showed that as the distances increased the JNDs got larger suggesting that it was more difficult to estimate greater distances. Additionally, JNDs for orientation and task were not significantly different meaning there was no difference in difficulty or variability when estimating distances between the different orientations or tasks.

### *Limitations and Future Studies*

The egocentric targets presented in this study were at a distance of 4, 5 and, 6 meters, as such they fall into the action space. Many studies looking at distance perception in VR use distance probes in this action area, however, most studies use motor based measurements or verbal estimate measurements. Due to the distances presented here being outside of the peripersonal space - where motor tasks such as reaching, grasping, or pointing could be used to measure distance perception - and the task used here not being motor based it is possible that action / perception processes are not invoked or differentially invoked, thereby, making it difficult to compare to previous literature in this field. A counter argument arising from the two systems theory, where some evidence supports the idea that judgments of spatial variables and visually guided actions are functionally dissociated and involve distinct processes, has been proposed where the use of motor based or visually guided tasks makes it difficult to differentiate between these action based process and those involved in visual space perception, therefore, calling into question the use of action tasks used to measure perception (Loomis & Philbeck, 2008). In support of the use of action based tasks to measure perceptual distance in the action space there is evidence that these measures covary with nonaction measures (Loomis & Philbeck, 2008; Thompson et al., 2011). Previous work comparing verbal reports and blind walking, perceptual matching tasks and blind walking, and shape judgments and blind walking found that these measures are similarly biased and closely covary; this supports the idea that action based tasks may be used to measure perceptual distance (Loomis & Philbeck, 2008; Thompson et al., 2011). Therefore, although the distances studied here are outside the peripersonal space where action/perception processes for this task may not invoked previous work suggests that compared to blind walking tasks perceptual matching tasks, as well as other nonaction tasks, may be similarly biased in this action space. Additionally, it is important to note that an advantage of using distances farther than 2 meters within a virtual environment is that accommodative mismatch is avoided; due to the fixed optical displays in HMD's variable focus is not available (Jones, Swann II, & Bolas, 2013).

Finally, a limitation of this study arises from the use of the method of constant stimuli psychophysical task. This method allows us to probe perceptual processes and extract a perceptual threshold for each participant, however, when using this psychophysical method it is important to have an idea of what the threshold will be and probe values around this threshold, in our study we assumed this threshold to be the presented probe (4, 5, or 6 meters). This however limited us in being able to fully assess participants whose perceptual thresholds fell farther away from the assumed threshold. Figure 10 shows  the psychometric curve for each participant for each task, distance, and orientation. We can see here that for some participants particularly in the L configuration task the perceptual threshold may be lower than we can extract here due to the range of distance probes tested. Future studies using this method or task may need to widen the range of distance probes to fully encapsulate the possible responses of participants.

Further future studies should try to understand the relationship between VR and distance underestimation with a particular attention to which tasks are being used to test distances. We showed in our study that the T-configuration task results in near accurate estimation of distances in VR, understanding why this task is unlike the others that have been previously used to test distances in VR may be an important factor in determining why misestimation in VR is common. Additionally, we showed that lying on one’s side can also influence egocentric distance perception. In future studies it may be beneficial to replicate our results to confirm the effect, as well as, look to see if this effect is persistent on both sides. Getting this information could add to the growing body of literature exploring how our vestibular system may be directly affecting the perception of space and objects around us.

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## Appendix

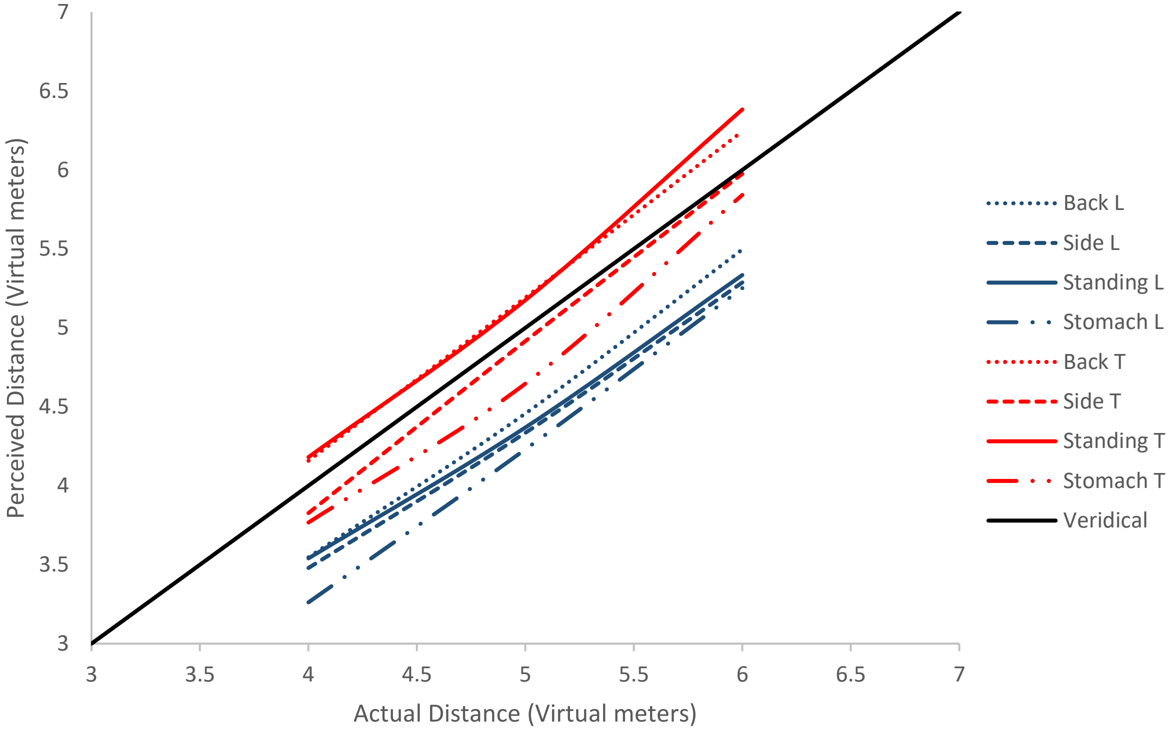

*Figure 9:* ***Perceived Distances for T and L Configurations at Each Orientation at 4, 5, 6 Meters.***

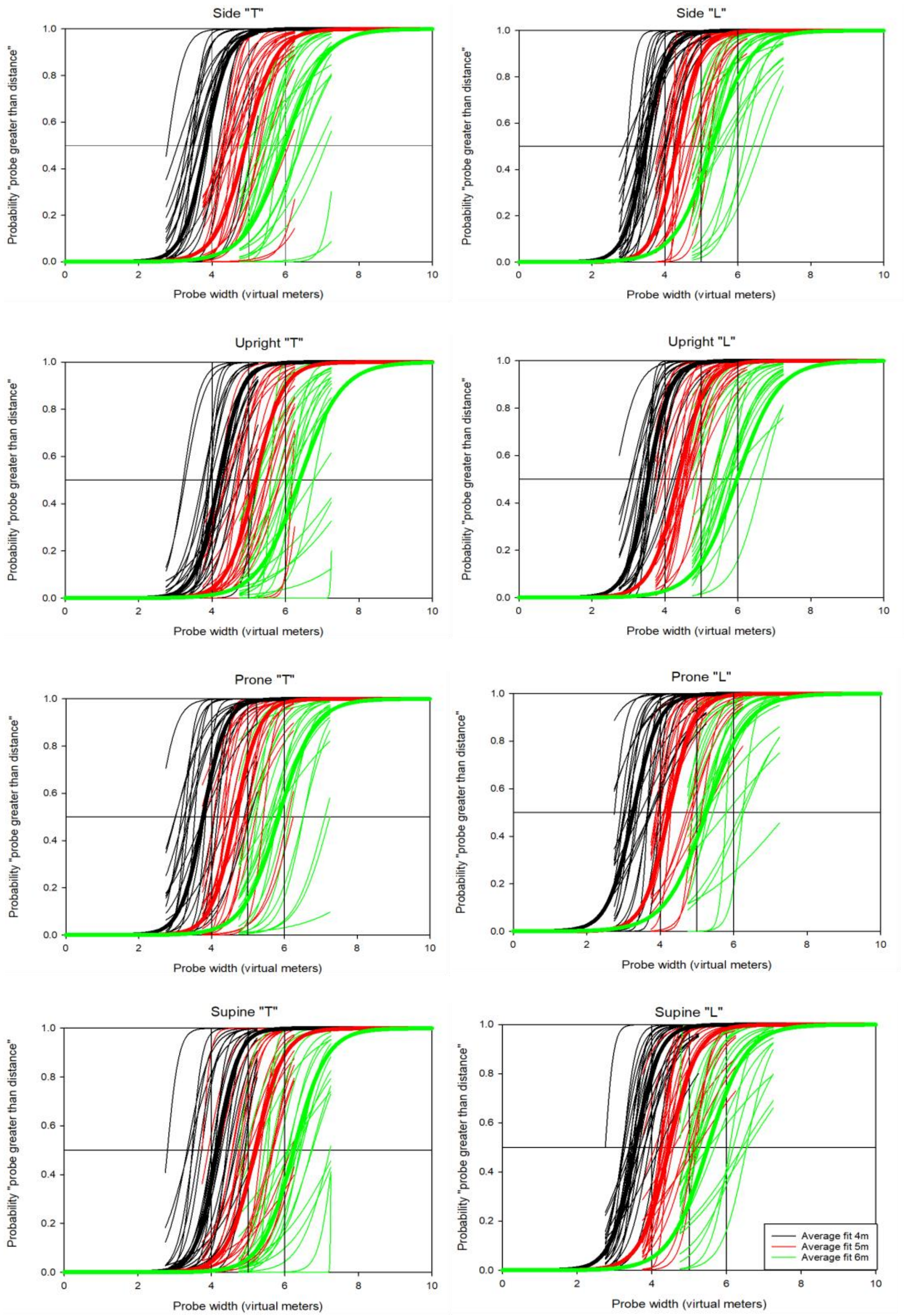

*Figure 10:* ***Psychophysical Curves for Each Participant at all Distances, Orientations and, Task****. Bold lines represent average at each distance within the corresponding orientation and task. Black lines represent the psychophysical curves at 4 meter probe distance, red at 5 meter probe distance and, green at 6 meter probe distance.*

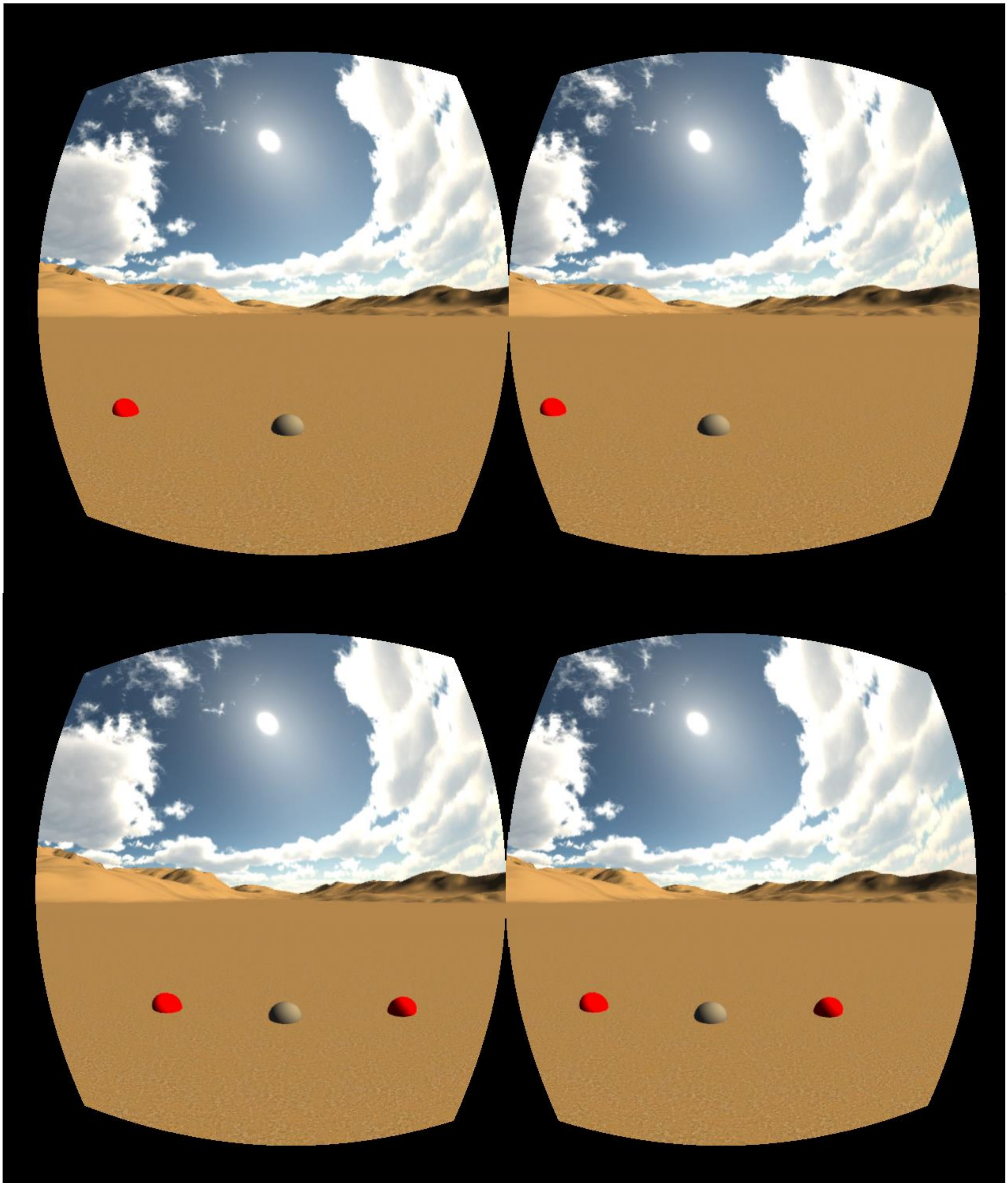

*Figure 11:* ***Virtual Environment and Psychophysical tasks at 4 Virtual Meters.*** *L configuration task above. T configuration task below.*

| Egocentric Distance (Meters) | Distance Between Red and Grey Probe (Meters) T Configuration | Distance Between Red and Grey Probe (Meters) L Configuration | T - Configuration Probe VA (Degrees) | L - Configuration Probe VA (Degrees) |
|---|---|---|---|---|
| 4 | | | | |
| | 1.375 | 2.75 | 18.97 | 34.51 |
| | 1.5 | 3 | 20.56 | 36.87 |
| | 1.625 | 3.25 | 22.11 | 39.09 |
| | 1.75 | 3.5 | 23.63 | 41.19 |
| | 1.875 | 3.75 | 25.11 | 43.15 |
| | 2 | 4 | 26.57 | 45.00 |
| | 2.125 | 4.25 | 27.98 | 46.74 |
| | 2.25 | 4.5 | 29.36 | 48.37 |
| | 2.375 | 4.75 | 30.70 | 49.90 |
| | 2.5 | 5 | 32.01 | 51.34 |
| | 2.625 | 5.25 | 33.27 | 52.70 |
| 5 | | | | |
| | 1.875 | 3.75 | 20.56 | 36.87 |
| | 2 | 4 | 21.80 | 38.66 |
| | 2.125 | 4.25 | 23.03 | 40.36 |
| | 2.25 | 4.5 | 24.23 | 41.99 |
| | 2.375 | 4.75 | 25.41 | 43.53 |
| | 2.5 | 5 | 26.57 | 45.00 |
| | 2.625 | 5.25 | 27.70 | 46.40 |
| | 2.75 | 5.5 | 28.81 | 47.73 |
| | 2.875 | 5.75 | 29.90 | 48.99 |
| | 3 | 6 | 30.96 | 50.19 |
| | 3.125 | 6.25 | 32.01 | 51.34 |
| 6 | | | | |
| | 2.375 | 4.75 | 21.60 | 38.37 |
| | 2.5 | 5 | 22.62 | 39.81 |
| | 2.625 | 5.25 | 23.63 | 41.19 |
| | 2.75 | 5.5 | 24.62 | 42.51 |
| | 2.875 | 5.75 | 25.60 | 43.78 |
| | 3 | 6 | 26.57 | 45.00 |
| | 3.125 | 6.25 | 27.51 | 46.17 |
| | 3.25 | 6.5 | 28.44 | 47.29 |
| | 3.375 | 6.75 | 29.36 | 48.37 |
| | 3.5 | 7 | 30.26 | 49.40 |
| | 3.625 | 7.25 | 31.14 | 50.39 |

*Table 1:* ***Visual Angle (degrees) for L and T Configurations at Each Probe Distance for 4, 5, and 6 Meter Egocentric Distances***