UPDATING DURING LATERAL MOVEMENT USING VISUAL AND NON-VISUAL MOTION CUES

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Abstract

Spatial updating, the ability to track egocentric positions of surrounding objects during self-motion, is fundamental to navigating around the world. Past studies show people make systematic errors when updating after linear self-motion. To determine the source of these errors, I measured errors in remembered target position with and without passive lateral movements. I also varied the visual (Oculus Rift) and physical (motion-platform) self-motion feedback. In general, people remembered targets as less eccentric with greater underestimations for more eccentric targets. They could use physical cues for updating, but they made larger errors than when they had only visual cues. Visual motion cues alone were enough to produce updating, and physical cues were not needed when visual cues were available. Also, people remembered the targets within the range of movement as closer to the position they were perceived before moving. However, individual perceived distance of the target did not affect their updating.

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John Jong-Jin Kim

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1.0. Introduction

1.1. General Introduction

Navigating around convoluted city streets comes naturally to most people, which shows how effectively people can keep track of their surroundings while moving. When moving, a person must update the position of surrounding objects relative to themselves in order to avoid or engage with them. This process is called spatial updating (Riecke, Heyde, & Bülthoff, 2005; Wang, 2017; Wolbers, Hegarty, Büchel, & Loomis, 2008). Spatial updating is an automatic and obligatory process that is a fundamental aspect of our everyday navigation and yet we still do not know how the brain carries out this task.

When updating the position of surrounding objects, a person first needs to know their own movement through space. Knowing their own movement requires integrating various sensory information, signals from visual, vestibular, somatosensory and motor systems (Greenlee et al., 2016; Harris et al., 2002; Medendorp, 2011). The visual system provides information about the relative movement of the surrounding environment as a person move through, and the vestibular system provides information about head movement from physical motion. The somatosensory system detects change in pressure on the skin, and the position and movement of joints and muscles, providing information on the position and movement of the limbs (proprioception). During active movement, efference copy (the internal copy of the efferent motor signal i.e., the commands to make limb movements) allows a person to prepare for the consequences of self-motion. However, proprioception and efferent copy both have a very variable linkage with the resulting self-movement. In situations such as riding a bicycle or driving a car, their input needs to be interpreted in context (Harris et al., 2002). Combining these processes allows a person to know their own movement and hence, theoretically, to predict surrounding earth-stationary objects' positions relative to them after and during movement (Medendorp, 2011).

How people gauge the positions of objects after moving is strongly influenced by their perception of the spatial structure of the surrounding environment, i.e., the egocentric directions and distances of the objects (Burgess, 2006; Wang & Spelke, 2000), and self-motion (Burgess, 2006). Any misperception of travel distance will lead to errors in computing the new egocentric locations of objects after a move. Such errors, however, can be corrected by visual information from the environment that allows an observer to derive object locations using allocentric references, i.e., landmarks (Burgess, 2006). To prevent people using such landmarks to derive object locations after a move, previous studies have deprived their participants of visual information by conducting updating experiments in the dark (Gutteling & Medendorp, 2016; Gutteling, Selen, & Medendorp, 2015; Klier, Hess, & Angelaki, 2008).

There is no shortage of literature looking into spatial updating as it is a fundamental and necessary ability for people's everyday lives (see Medendorp, 2011 for a review). How the position of an object relative to an observer changes differs for rotational and linear movement: updating an object's position during linear movement requires more complex computation because only linear movement alters the distance between the observer and object (Medendorp, 2011). Many researchers have investigated the contribution of different sensory cues, such as visual and vestibular cues, on spatial updating. However, most of these studies have used rotational movements, specifically yaw (Riecke, Cunningham, & Bülthoff, 2007; Riecke, Heyde, et al., 2005; Wang & Spelke, 2000; Wraga, Creem-Regehr, & Proffitt, 2004) and some forward movement (Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Li & Angelaki, 2005), but did not consider linear lateral movements. Klier, Hess, and Angelaki (2008) looked at updating after passive linear translations, but did not test self-motion cues separately and only used targets directly in front of the observer. Not only that, no past research, as far as I know, has considered consequences of a person misperceiving the spatial scale of the environment when updating.

In this thesis, I show that people can use physical motion cues for spatial updating but may not need them when visual cues are available after lateral movement, and their remembered target location depends on the range of movement. Results also show that misperceived scale of environment, in terms of perceived distance, may not influence updating.

1.2. Self-motion Cues

1.2.1. Vision.

When a person moves, the visual scene is displaced relative to them. The pattern of visual movement that this creates, potentially giving information about the person's movement, is called optic flow (Gibson, 1950). Depending on the nature of a person's movement, different patterns of optic flow are generated. Pitch, roll, or yaw rotation (*Figure 1A*) generate a simple angular displacement of all objects in the field. Translational motions, up-down, lateral, and fore-aft (*Figure 1B*) generate more complex patterns that radiate out from the direction of travel. During head rotation, a person looking straight ahead sees vertical flow during pitch (*Figure 1C*), circular flow during roll (*Figure 1E*), and horizontal flow during yaw (*Figure 1D*). During linear movement, the person sees vertical flow during up-down movement (see *Figure 1C*), horizontal flow during lateral movement (*Figure 1D*), and expansion/contraction of the view during fore-aft movement (*Figure 1F*). During linear movement, objects in a three-dimensional visual scene move at different angular rates depending on their distance to the observer creating parallax.

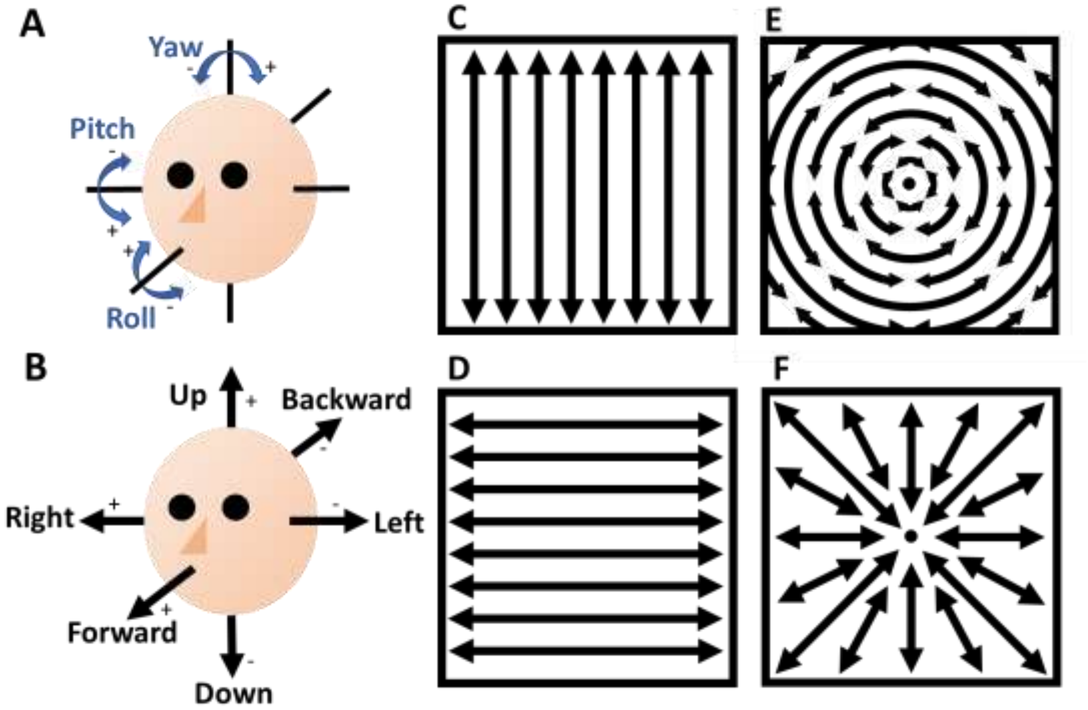


Figure 1: Head movement and optic flow: A – head rotations, B – vertical flow (up/down), C – horizontal flow (left/right), D – circular flow (clockwise/counter-clockwise), E – forward/backward flow (expansion/contraction). Note: these are simplified diagrams of the visual flow one may observe during self-motion and only illustrate the overall direction of motion of images created by various movements.

Vection.

Being exposed to visual motion can also cause vection, the sensation of self-motion induced by optic flow (Howard & Howard, 1994). Such an illusion can occur from looking at a moving train through a window or when viewing virtual reality (VR) displays via a headset. Peripheral vision plays a key role in vection for both rotation (Brandt, Wist, & Dichgans, 1975) and linear vection (McManus, D’Amour, & Harris, 2017), although central vision can also produce strong linear vection (Andersen & Braunstein, 1985). Displays providing wide field of view (FOV), such as dome-shaped virtual reality screen or three monitors aligned next to each other, were found to generate stronger vection intensity, shorter vection onset times, and longer vection duration than general monitor or a projector screen (Keshavarz, Speck, Haycock, & Berti, 2017). Head-Mounted VR devices that provide wide FOV, such as the Oculus Rift, have been found to produce reliable vection in terms of strength and latency (Kim, Chung, Nakamura, Palmisano, & Khuu, 2015), making VR a useful research tool to expose people to movements that would be difficult or impossible to produce in the real world, e.g., experiencing long distances or prolonged accelerations, or producing incongruent motion cues between visual and physical cues. Visual information alone, especially if seen with a restricted view can be ambiguous. For example, central optic flow patterns can be very similar even though they are created by different head movements (e.g., pitch and up-down translation, or yaw and lateral translation). Therefore, integrating visual cues with other information, such as vestibular cues, is often required to interpret the visual information and accurately determine the self-motion that generated it.

1.2.2. Vestibular System.

The vestibular system comprises two main organs, the semicircular canal system and otolith organs (see *Figure 2*). Semicircular canals consist of superior, posterior, and lateral canals responding to the rotational acceleration of the head. The combined signals from all three canals produce the sensation of the head rotations: pitch, roll, and yaw (see *Figure 1A*). Otolith organs are made up of the utricle and saccule, which respond only to linear acceleration of the head: up-down, lateral, and fore-aft (see *Figure 1A*). In this thesis, only linear movements are considered, specifically lateral movements. During lateral linear accelerations the utricle is most sensitive; some hair cells on utricle are excited and some are inhibited, coding the direction and amplitude of the head acceleration.

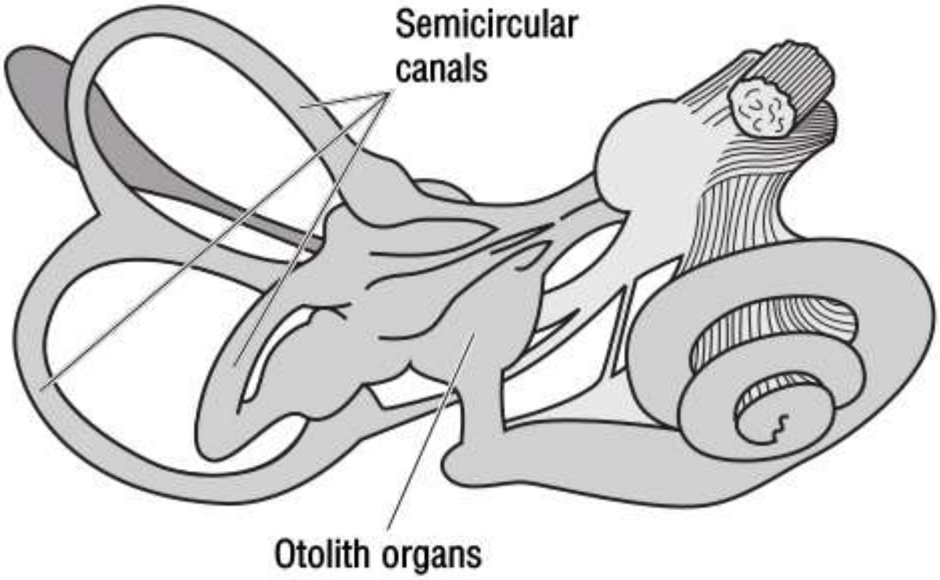


Figure 2: Vestibular System showing the layout of the otoliths and semicircular canals (vestibular system. Retrieved from https://www.wpclipart.com/medical/anatomy/ear/vestibular_system.png).

However, vestibular information alone is also ambiguous. Semicircular canals and otolith organs only provide information about changes in head movement, i.e., acceleration, without any context to how the movement is related to the world, and the otolith organ cannot distinguish linear acceleration due to head translation from the acceleration of gravity (Angelaki & Cullen, 2008). The vestibular system is only responsive to accelerations from which velocity and position need to be deduced. It is not stimulated by moving at constant velocity making vestibular cues unreliable during these periods. To reduce some of these ambiguities, vestibular signals need to be integrated internally using information from both the semicircular canals and the otolith organs (Merfeld, Park, Gianna-Poulin, Black, & Wood, 2005a, 2005b), as well as with visual and proprioceptive information (Harris et al., 2002; Hlavacka, Mergner, & Bolha, 1996).

1.3. Updating After Self-Motion

When moving, the egocentric location of the surrounding objects relative to the person need to be updated in respect to the movement. During rotation, the egocentric distance of the object remains constant. Therefore, the only updating required during rotation is the egocentric direction of the object. Riecke, Heyde, & Bülthoff (2005) rotated people as fast as 16.3°/s, and compared the angular pointing errors people made after yaw rotations either stopping at a new orientation or returned to the original orientation. People made less than 6° errors in both cases, which suggests people can infer new target directions after a rotation up to 57° in angle.

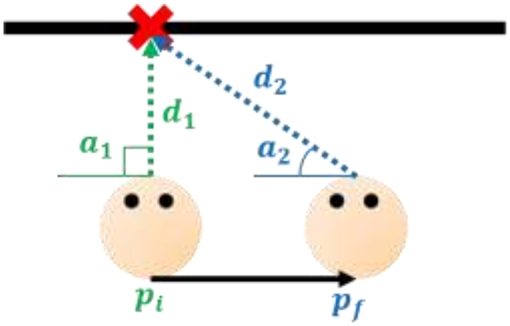


Figure 3: Change in egocentric target position during lateral movement. a_1 = visual angle of target when person is at the initial position (p_i) before moving, a_2 = visual angle of target when person is at the final position (p_f) after moving, d_1 = target distance from the person at p_i, d_2 = target distance from the person at p_f.

During linear movement, however, more complex computation is required. The egocentric distance and direction of an object changes depending on the direction and motion profile of the person’s movement. For example, the egocentric direction of the object will not change at all as a person moves towards or away from the object. In this special case the only updating required is to the egocentric distance of the object. When a person is keeping track of an object in front of them while moving laterally, both direction and distance of the target change (see *Figure 3*). First, the person may make error from the mis-perception of the initial scene.

Then there may be updating errors made during the movement due to mis-updating of the direction, distance to the target, or both. These errors can be attributed to the misperception of self-motion in which a person misestimates their travel distance. For example, the new object position after movement is estimated as further displaced in the direction of the movement with underestimated travel distance, and in the opposite direction of the movement with overestimated travel distance when tracking objects in front during lateral movement (see *Figure 4*).

Klier et al. (2008) found people can update the locations of world-fixed visual targets following passive full-body linear translation in dark. However, people still made systematic errors in which they overestimated the angular change of the target after forward/backward movements (gain of 1.12 ± 0.45; a value of 1 indicates perfect updating and a value of 0 indicates no updating) and underestimated after lateral (gain of 0.84 ± 0.28) and downward movements (gain of 0.51 ± 0.33). In a study by Gutteling and Medendorp (2016), people again made systematic underestimation of the angular change of the target (gain of 0.61) when estimating world-fixed target location after passive full-body lateral translation. If only perception of self-motion is considered, both results suggest that perception of self-motion

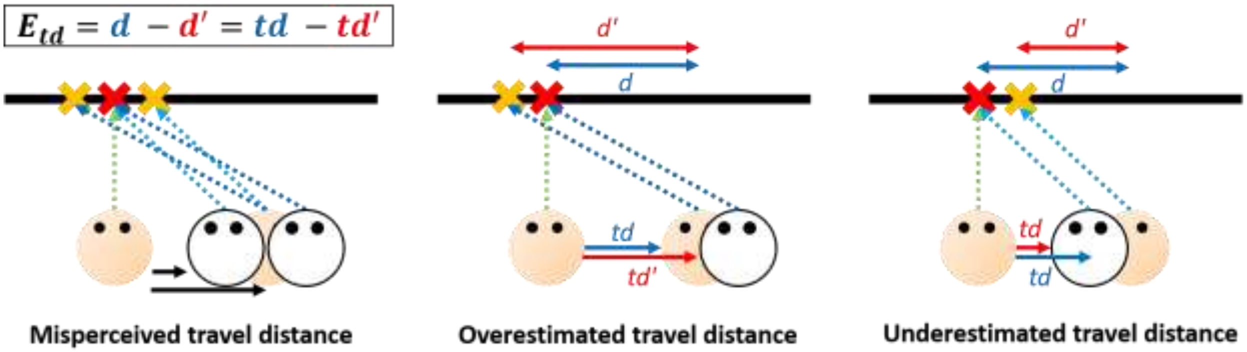


Figure 4: Errors in updating target eccentricity due to misperceived travel distance. E_{td} = errors due to misperceived travel distance, *d* = actual target eccentricity, *d'* = perceived target eccentricity, *td* = actual travel distance, *td'* = perceived travel distance.

during lateral translation may be underestimated as generally found in the past (Berthoz, Pavard, & Young, 1975; Tremblay, Kennedy, Paleressompoulle, Borel, & Mouchnino, 2013).

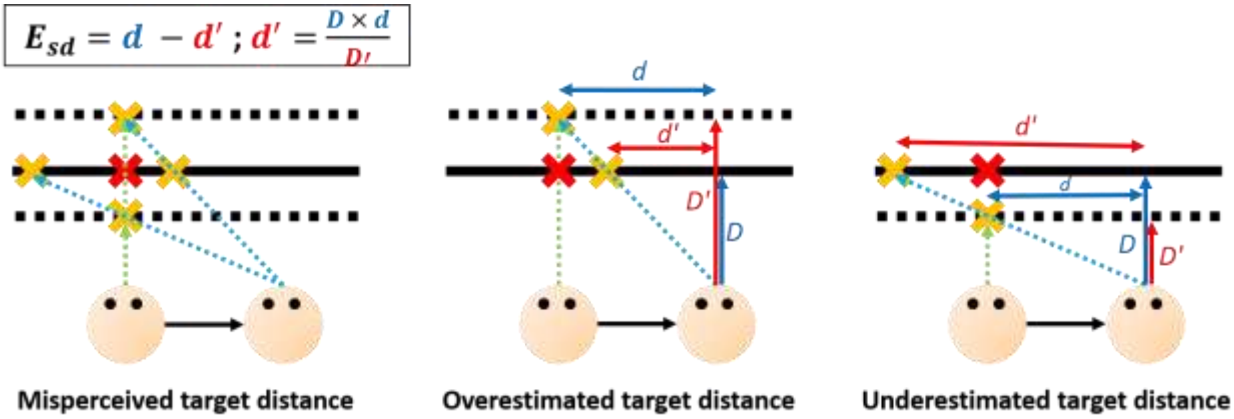
Studies on visual and vestibular cues to the perception of self-motion have quite consistently shown that people are more accurate in judging their self-motion when both cues are available (Greenlee et al., 2016; Ter Horst, Koppen, Selen, & Medendorp, 2015). However, the roles of visual and vestibular cues on spatial updating have been associated with conflicting views. In a study by Riecke et al. (2005), it was demonstrated that during rotation, specifically yaw, visual information alone without physical motion, of a naturalistic scene with familiar landmarks, is sufficient for updating target direction. In a following study, Riecke et al. (2007) found that pure optic flow pattern of a gray fractal texture of yaw rotation was insufficient to be used for updating, even with physical motion cues available. When Riecke, Sigurdarson, and Milne (2012) combined rotational and linear movements, in a visual-only passive movement simulation to test whether people are able to update target position, people were unable to update during rotations if the visual scene did not contain landmarks familiar to the viewers, even when physical motion cues were added. During the linear movement portion of the simulation, people were able to update without physical motion cues or familiar landmarks. From these findings, they concluded that: (1) physical cues are incapable of inducing spatial updating during rotation; (2) updating during rotation with visual cues alone requires familiar landmarks; (3) during linear forward motion, visual cues alone are enough for spatial updating. Whitney, Westwood, and Goodale (2003) found that people were less accurate at pointing at a world-fixed targets after a yaw rotation when the background (surrounding light-emitting diodes (LED)) was only intermittently or not visible for both whole-body rotation, fixating on a point moving with them, and eye movement (smooth pursuit), only following the moving point with their eye. When the background was not visible, people made systematic errors in the direction of rotation, further suggesting that people require visual motion cues for correctly updating target locations after yaw rotation and physical cues are not enough for updating after rotation.

Harris, Dyde, and Jenkin (2005), however, showed that visual cues alone are not sufficient and non-visual cues, including physical motion, proprioception, and efference copy, may be required to update object positions correctly after linear (vertical and horizontal) movement. Study by Wraga et al. (2004) showed that physical motion provide advantage for updating during rotation, but did not find advantage of active movement control, i.e., proprioception, and efference copy. Wei, Li, Newlands, Dickman, and Angelaki (2006) found updating performance of the trained rhesus monkeys was compromised after the vestibular labyrinths were lesioned bilaterally for both rotation and translation. They showed some recovery after a week, but their updating capacity was still compromised compared to the pre-lesion performance even after 4 months, further suggesting vestibular cues are indeed used for updating. Physical cues alone, however, seems to be not accurate enough to be used alone (Blouin, Labrousse, Simoneau, Vercher, & Gauthier, 1998). Updating may also depend on the observer’s experience and the information available at the time. For visual cues, people seem to require visually moving natural scene during both rotation and translation, but during rotation identifiable landmarks are needed. Based on these results, spatial updating is not a simple process and motion cues alone (visual or physical) may not be enough to correctly update object positions and moving observers may require additional spatial information such as landmarks.

In terms of the contribution of the motion cues, however little it may be, it is plausible that visual and physical cues are weighed differently when used for updating during rotation or linear movements. People reweigh visual and vestibular cues based on their reliability when determining self-motion, and they tend to over-weigh vestibular cues (Fetsch, Turner, DeAngelis, & Angelaki, 2009). People might over-weigh vestibular cues for certain movements when visual cues are ambiguous (see section 1.2.1). The contribution of visual and vestibular cues may even differ between the direction of translation (vertical, horizontal, and fore-aft). Therefore, studies investigating spatial updating may need to look at each movement direction separately to properly understand the contribution of each senses (e.g., visual and vestibular senses for the present study).

1.4. Updating in a Virtual Environment

Perception of the size and the structure of the environment relative to the scale of your own body influence your perceived self-motion. Distance compression in VR is a well-known phenomenon in which the distance of objects is perceived as closer than intended by the system designer (Peer, 2017). Misperceived distance, i.e., size of the environment, may lead to mis-updating the object position after movement. Overestimated target distance should result in the underestimation of the new object eccentricity, and underestimated target distance should result in the overestimation of the new object eccentricity after movement (see *Figure 5*).



Misperceived target distance Overestimated target distance Underestimated target distance

Figure 5: Errors in updating target eccentricity due to misperceived target distance. E_{sd} = errors due to misperceived target (stimulus) distance, *d* = actual target eccentricity, *d'* = perceived target eccentricity, *D* = actual target distance, *D'* = perceived target distance.

Despite the misperception of space in virtual environment, VR is a useful study tool to measure people’s responses during experiments. VR displays produce convincing vection (Kim et al., 2015), as already mentioned in section 1.2.1. An experimenter has vast control over the test settings, manipulating the virtual environment into different orientations and sizes, and even defying the laws of physics. Also, artifacts due to testing in VR should cancel out when results are compared between conditions within VR. It is important, however, to make sure people’s responses in VR are identical to their responses when performing comparable tasks in the real-world if VR is to be useful for, for example, training for tasks to be operated in the real world. Comparing people’s performance in virtual environment to the real-world environment allows quantifying the differences in their experiences between the two environments.

I conducted three experiments where people had to remember and point at the location of a world-fixed target after passive lateral movement within a virtual environment. In experiment 1, I confirmed the feasibility of the test method of pointing at remembered target location, concluding that visual feedback was required for any degree of accuracy. Experiment 2 showed that updating during illusory, visually-induced lateral movement (vection) depends on target eccentricity. Finally, in experiment 3, I show that physical self-motion cues can be used for updating, although they are not used when visual self-motion cues are available. I will also briefly discuss the result of correlating individual perceived distance in the environment and the errors people made in updating.

1.5. Hypothesis

I hypothesized that:

1. The errors in remembered target locations will be smaller in magnitude when both visual and physical cues are available during passive movement when compared to when only visual cues are available.
2. The errors in remembered target locations will be smaller in magnitude when both visual and physical cues are available during passive movement when compared to when only physical cues are available.
3. The error differences in remembered target locations will be smaller in magnitude when only physical cues are available during passive movement when compared to the distance traveled.
4. The closer a person perceives a virtual scene, the more eccentric their remembered targets location will be.

2.0. General Methods

In this section I will outline the methods that are common to each of the experiments that contribute to this thesis. Further details can be found in the specific methods preceding each experiment.

2.1. Visual display

All tests were conducted in virtual reality (VR) using an Oculus Rift Head Mounted Display (HMD). The HMD used was Oculus Rift Consumer Version 1 (CV1) which provided resolution of 1080×1200 pixels per eye, maximum 90 Hz refresh rate, 110 degrees FOV, and weighed 470 grams (see *Figure 8a*). Participants also used an Oculus Touch controller in their right hand to point at target positions.

In order to track the head and hand motion, I tracked the HMD, and the controller positions and orientation using Oculus Sensors. Two sensors were set up on the front wall for Exp 1 and 2. One additional sensor was set up on the right wall in Exp 3, totaling three sensors (see *Figure 6*). The HMD was powered from a Windows 10 computer, model Alienware 17 R4 with Intel® Core™ i7-7700HQ CPU @ 2.80 GHz, 16.0 gigabyte RAM, and NVIDIA GeForce GTX 1070 graphics card. The VR environment was built in Unity game engine with scripts programmed with C# language to run the test.

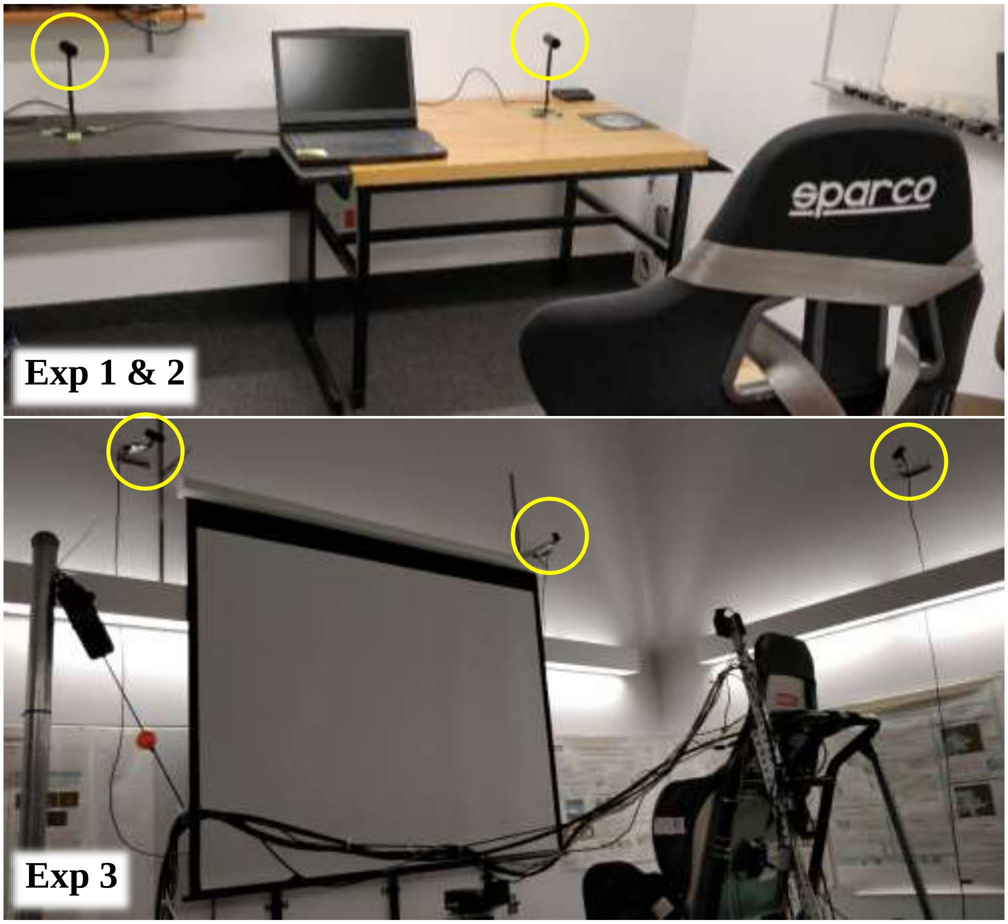


Figure 6: Oculus Sensors Set-up

2.2. Measuring perceived spatial scale in VR

To gauge participants' perception of spatial scale in the virtual environment, I measured participants' distance perception by exploiting size-distance dependency. The distance of an object can be inferred from the retinal image of the object (Collett, Schwarz, & Sobel, 1991; Kunnapas, 1968) which is directly correlated with its physical distance. However, the topic of size-distance invariance has been found to be complicated and messy where the reported perceived sizes may be prone to biases (Baird & Biersdoftf, 1967; Carlson, 1960; Foley, 1972). Despite the controversies, for the purpose of quantifying each participant's perceived target distance I assumed the perceived distance to be directly dependent on the perceived visual size.

I measured the perceived size of a test object and from that calculated the perceived distance to the virtual screen in the virtual environment (Harris & Mander, 2014; Kim, McManus

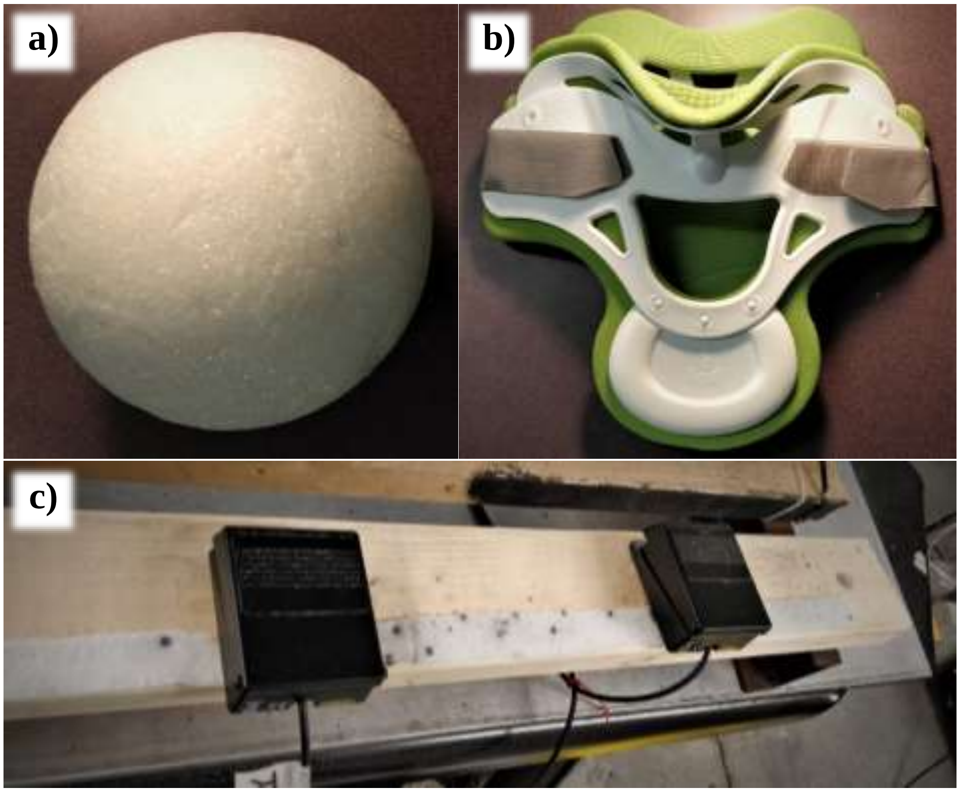


Figure 7: a) Reference ball (12.5 cm dia.) – Styrofoam. b) Neck Brace – 4098 OPPO Cervical Collar. c) Foot pedals.

& Harris, in prep.). Participants had to compare the size of a visually presented spherical ball to that of a physical reference ball held in their hands. The reference ball (see *Figure 7a*) was a white Styrofoam ball, 12.5 cm in diameter. After comparing sizes, they used foot pedals (see *Figure 7c*) to indicate whether the image visual ball was larger or smaller than the reference ball.

2.3. Physical motion

Physical motion was produced using York University's MOOG Motion System (MMS), model 6DOF2000E-170E122A, a motion base platform that can move with six degrees of freedom (see *Figure 8b*). I restrained participants' neck movement using a neck brace, 4098 OPPO Cervical Collar (see *Figure 7b*), to prevent them from tilting or injuring their neck during movement. MMS was controlled from a Windows 10 computer, model Dell with Intel® Core™ i7-2600 CPU @ 3.40 GHz, 8.0 gigabyte RAM, and AMD Radeon HD 5450 graphics card. The motion profiles were programmed in Unity game engine with C# language.

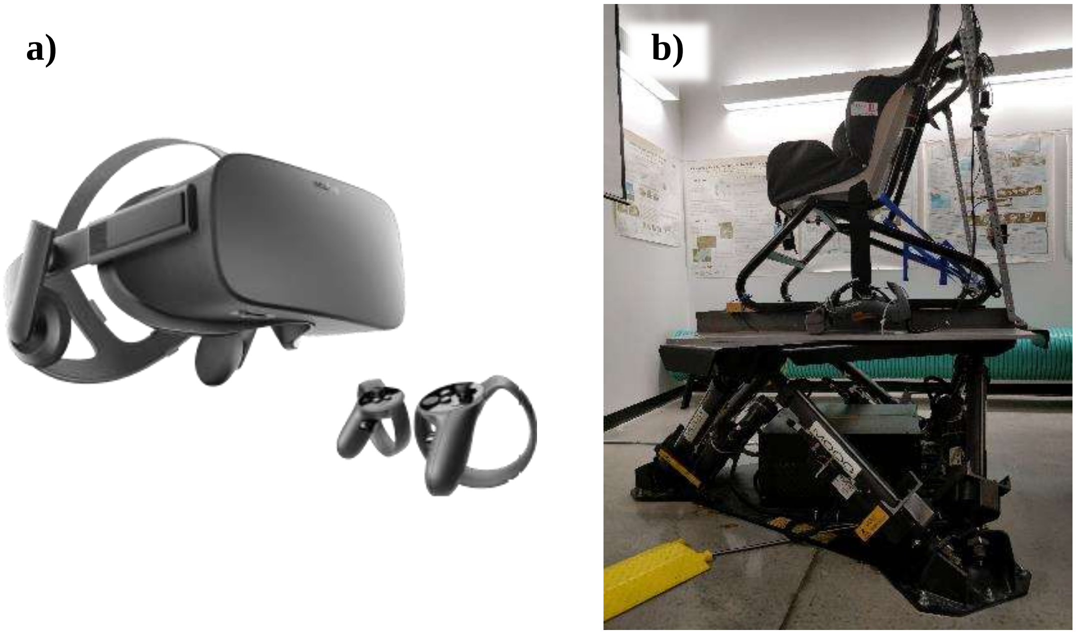


Figure 8: a) Oculus Rift virtual reality headset with built in display screens and Oculus Touch controllers. b) MOOG Motion System – motion base platform at York University.

The movement profile was programmed to be a linear lateral motion (programmed in C# executed using Unity at 60Hz). MMS accelerated rapidly at the maximum acceleration possible, either to right, or to left. At the end of travel, MMS decelerated rapidly until stop. See *Figure 9* for the sample motion profile of the MMS.

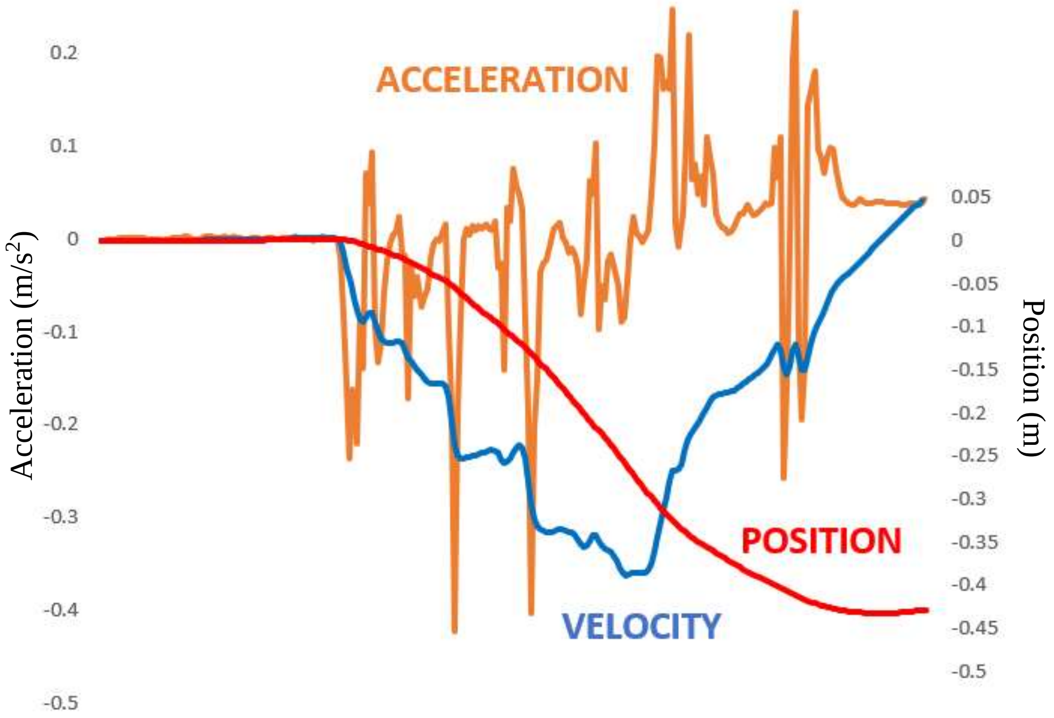


Figure 9: Sample motion profile of the MMS platform – moving to left: **Orange** – the position of the platform from the one end to the other, **Blue** – the speed of the platform at a given time, **Red** – the acceleration.

2.4. Visual Stimuli

2.4.1. Test environment.

The test environment in VR was an accurate, detailed virtual version of the test room (the MMS room used for experiment 3) recreated in Unity Engine (see *Figure 10*). All the distances stated throughout this paper are intended distances in the virtual environment built in Unity Engine (1-unit length in Unity = 1m). The real and virtual rooms featured a large projection screen in front of the subject with a plan to compare real-world and virtual-world motions using stimuli that were as close as possible to identical. The real-world studies were not conducted due to technical issues.

All visual stimuli were displayed on a simulated screen in VR at a set distance (2 meters for experiment 1 and 2, 1.75 meters for experiment 3) away from the camera, i.e., the eyes.

Figure 10: Virtual environment of the test room.

2.4.2. Distance perception test display.

An image of a grey sphere (*Figure 11a*) was used as a visual size to be compared to a physical size of a real physical reference ball (see *Figure 7a*) during distance perception measurement. The size of the grey balls started with 7.5 cm (small) and 80 cm (large), then varied depending on the participants’ responses (see below).

2.4.3. Updating test display.

An image of a tennis ball (*Figure 11b*), diameter ≈ 67 mm, approximately 2° in angular size, was projected onto the virtual screen and used for the updating test (see below). During the lateral translation updating test, randomly generated dots were displayed on the screen (1.5 meters x 2 meters). The density of the dots was 50 dots per m^2: the maximum number of dots I could display without the HMD lagging (from simple visual observation). The size of the dots varied between 1.0 cm and 6.5 cm (see *Figure 12*).

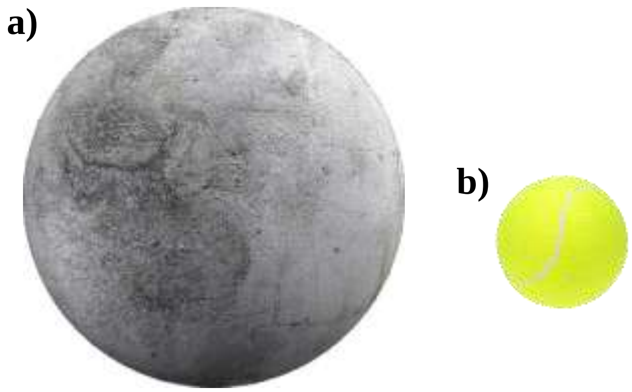


Figure 11: Visual targets - image of a grey ball (distance perception test target) and image of a tennis ball (updating test target).

2.5. Procedure

Participants sat either on a chair on the MMS (see below) or in an earth-fixed racing car chair and put on the HMD in which they viewed the virtual environment and the stimuli. The participants either wore a neck brace (Exp 3) or their HMD was fixed to the chair with a strap (Exp 1, and Exp 2) to restrict head-movement. Before each of the three experiments, participants completed the distance perception test.

2.5.1. Distance perception test.

During the distance perception test, participants were shown an image of a grey ball displayed on the simulated screen in VR. They held the physical reference ball with both of their hands. Participant compared the size of the grey ball image on the screen to the size of the reference ball in their hands, then responded using foot pedals as to whether the image was larger or smaller than the reference – right pedal for larger and left for smaller. The size of the image was changed based on the participants' response to the previous presentation (either "larger" or "smaller") under the control of a Parameter Estimation by Sequential Testing (PEST) function (Taylor & Creelman, 1967). I used two separate PEST functions where the visual size started either small or large (see section 2.4.2). Each PEST function stopped after a fixed number of trials (25 trials; the number of trials found to be enough for responses to stabilize in the pilot).

2.5.2. Pointing Training.

Participants also went through a training session to get familiar with using the Oculus Touch controller before the main experiment started. During the training session, an accurately sized image of a tennis ball was presented on the virtual screen as a target. Participants held the controller with their right hand. Then they had to point at the target (a red dot appeared on the screen where they were pointing with the controller) and press a button on the controller to hit it. For the first 30 trials, the target was visible during the entire trial. For the last 20 trials, the target disappeared after 0.5 seconds and participants had to remember the location of the target and point at that location on a blank screen. Participants received feedback as to whether they correctly hit the target –a high-pitched ping if they hit the target or a low-pitched ping if they missed. After 50 trials, they were tested without feedback and only had 1.5 seconds to hit the target. To pass the pointing test, they had to hit the target at least 16 times out of the 20 trials (80%

accuracy). If the participant passed the test, they moved onto the experiment. If they did not pass the test, they went back to the training session then were tested again. Participants that could not pass after 3 tries were removed from the experiment.

2.5.3. Updating test.

During the experiment, participants were instructed to look straight at the simulated screen in the virtual environment. For each trial, a bell sound was played to let participants know the trial was starting. Then a fixation cross was displayed in the middle of their visual field which they fixated (see *Figure 12A*). After 0.5 seconds, a visual target (the image of a tennis ball) appeared for 0.5 seconds (see *Figure 12B*). After the visual target disappeared, randomly generated dots were shown on the screen (see *Figure 12C*) as participants were either stationary or passively moved laterally (to left/right). There were two possible starting test positions for the observer – either on the left or right side of the screen (see stimuli section of each experiment). The initial starting position was selected randomly, then alternated between the two positions. The movement direction depended on the observer starting position, moving towards the opposite observer position (see *Figure 12D*). After the movement, or after the idle period in the stationary condition, the screen went dark and a second bell sound was played. When the participants heard the second bell, they pointed at the remembered target location with the controller and pressed button A with their thumb. The intersection points between the participant pointing line and the plane at the screen distance was recorded as participants' remembered target location.

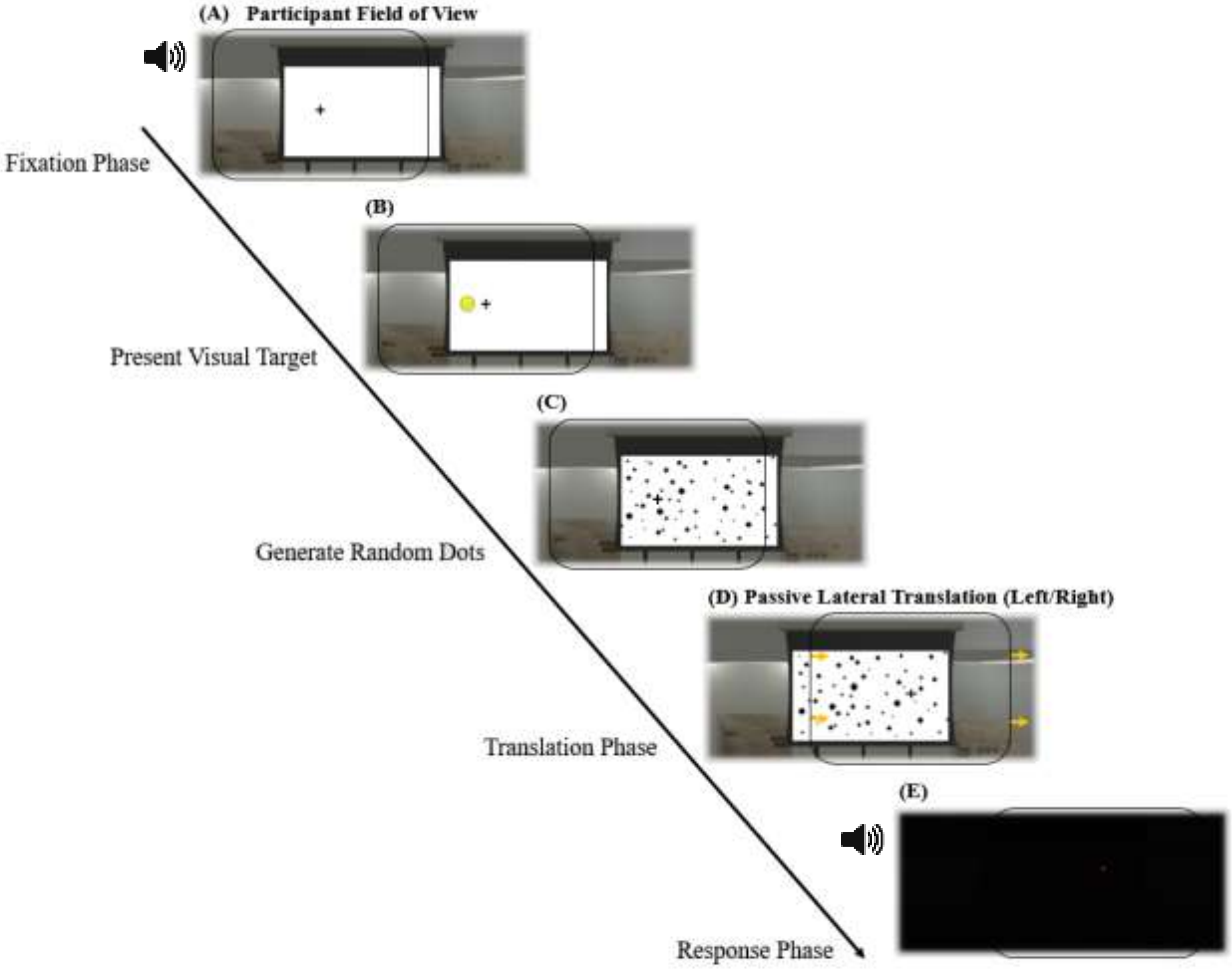


Figure 12: Experimental procedures – (A) Participant fixated on the fixation cross for 500ms. (B) Visual target presented for 500ms. (C) Randomly generated dots appeared on the screen after the visual target disappears. (D) Participant were either stationary for a set period or passively moved laterally. (E) The screen turns dark. Participant then moves the indicator target to the remembered location of the visual target as fast as they can.

2.6. Data Analysis

The accuracy of people's updating was measured by looking at the errors they made when pointing at remembered target locations after moving. Errors were calculated by subtracting the actual target position from the remembered target location (see *Figure 13*). To quantify the accuracy of their updating, I measured the errors people made when they pointed at remembered target locations after an idle period (without moving) or moving under various conditions.

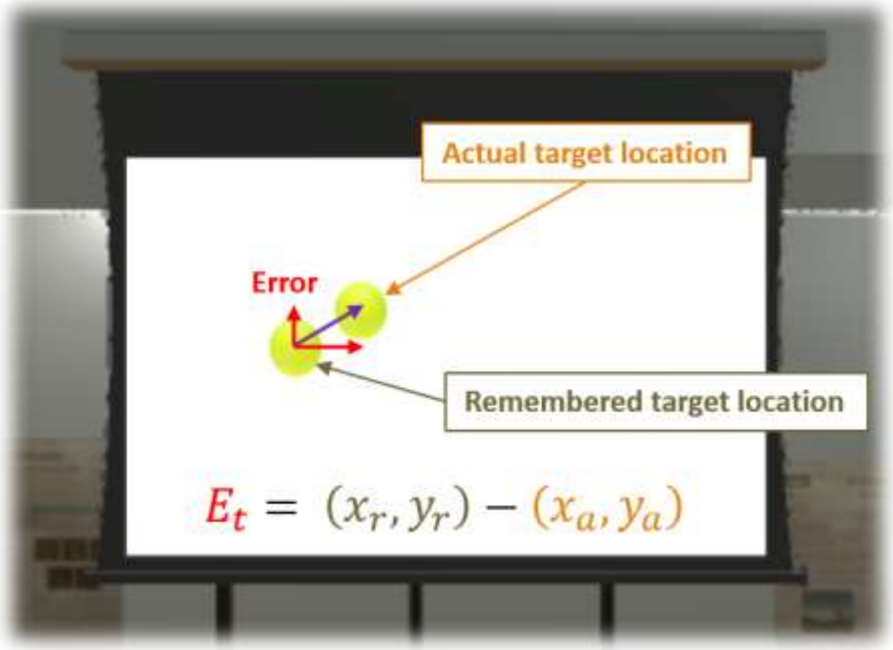


Figure 13: Errors in remembered target location. This error is calculated by subtracting actual target location from the observer's remembered target location: E_t = total error made, in vertical and horizontal, when remembering and pointing at the target location, (x_r, y_r) = remembered target location (x_r is the horizontal location, and y_r is the vertical location), (x_a, y_a) = actual target location (x_a is the horizontal location, and y_a is the vertical location)

2.6.1. Outlier analysis.

Each condition was tested for multiple trials (see experimental design sections for each experiment for the number of trials). Error value for each trial deviating greater than 2.5 standard deviation from the overall mean error of each condition was considered as outlying data point and removed from the data set. After removing all outlying data points, the mean errors for each condition for each participant was calculated giving them a set of mean errors for each condition.

If all the data points of any condition for a participant were removed, resulting in a missing mean error for that condition, the participant was considered as an outlier and removed from data analysis.

2.6.2. Updating test.

Remembered target location errors (E_{TL}) were measured as the horizontal distance (in meters) between the actual target location and the participant-remembered target location for each trial ($E_{TL} = x_r – x_a$; see *Figure 13*).

When there was no effect of observer position (left or right), remembered target eccentricity errors (E_{TE}) were collapsed across direction and the mean used for analysis. E_{TE} was calculated by multiplying both the target eccentricity and the E_{TL} by minus 1 for experiments in which the observer was on the right side on the testing space during the response phase. Doing so brings the error values to the same side, allowing me to look at the errors as a function of target eccentricity with positive numbers corresponding to “eccentricities in the direction of travel”. All error values of all trials within a condition (see each experiment for the conditions used) were averaged for each participant.

To evaluate the effect of movement, I used the difference in errors between the movement conditions and the static condition (E_D). To calculate E_D, the mean of $\mathrm{E_{TL}}$ of the static condition was taken as a baseline for the errors related to target eccentricity. Then the baseline errors were subtracted from each E_{TL} from the movement conditions at each target, from the corresponding response position, to reveal errors due to movement; see Equation 1.

$$E_D = E_{TL_M} - E_{TL_S}\ ; \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots \ (1)$$

E_D = difference in errors between movement condition and static condition for the target

E_{TL_M} = errors in remembered target location for movement condition for the target

E_{TL_S} = errors in remembered target location for static condition for the target

I used IBM SPSS Statistics (Version 24) to perform Linear Mixed Model analyses, comparing the errors to assess the effect of observer movement and target eccentricities. I used family-wise error rate of .05 for all analyses, controlled by seed-based d mapping (SDM) technique.

2.6.3. Perceived distance test.

The perceived screen distance was calculated from the perceived size of the projected visual grey ball when it was matched to the size of the reference object in the distance perception test. The average between the end values given by the PEST from each of the two starting sizes (small and large) was used as the measure of the perceived size of the visual ball. The perceived distance of the screen (*D'*) was calculated using the equations and geometry given in *Figure 14*. Errors in target distance (in meters) were then calculated by subtracting the intended screen distance from the perceived screen distance.

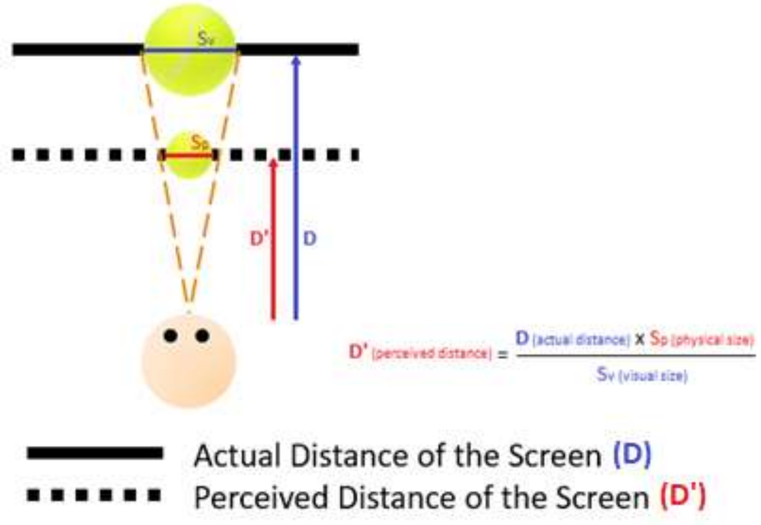


Figure 14: Geometry for actual distance vs. perceived distance based on the perceived visual ball size.

I analyzed correlation between participants' perceived distance errors ($D' - D$) and their remembered target eccentricity errors (average of E_{TE}s for all targets) using IBM SPSS Statistics (Version 24).

3.0. Experiment 1

In experiment 1, I evaluated the feasibility of using a hand-held controller as a response tool for participants. I presented participants with a target on a virtual screen for a short period time, then visually moved them either to the left or to the right. Participants had to remember where the target was on the screen and point at it using a hand-held controller. This was important because any errors due to using a controller would contaminate the measured error values, making it difficult to interpret the source of errors.

I also wanted to test how reliably participants could point at targets without visual feedback of their pointing location. When participants must point at a target in complete darkness to prevent them from using the environment, such as the edges of the screen, as reference to remembering target location. However, if they could see their pointing location by having a pointer visible, participants can easily detect the edges of the screen by simply moving the pointer across them. I varied how much information participants were given about where they were pointing (indicated with a red dot projected on the display) or not.

Although the method of pointing without a pointer would be the best practice to avoid participants from using features of the environment as a reference, I hypothesized that the remembered target location errors would be greater when a pointer was not shown compared to when the pointer was present.

3.1. Participants

Nine females and five males (14 total), average age of 28.07 years (*SD* = 12.90), participated in the study. Participants were either recruited for the study via York University's Undergraduate Research Participation Pool (URPP) and given course credit or were graduate students or faculty members from the school. All participants had normal or corrected-to-normal vision. Participants self-reported as right handed, except one participant who was ambidextrous. All the participants gave informed consent. The experiment was approved by the York University's Ethics Review Board and was carried out using the principles of the Treaty of Helsinki.

3.2. Stimuli

Three target positions were spread horizontally at -0.5m, 0m, and +0.5m from the center of the screen with the observer positioned either to the left (L) or on the right (R), that is in line with the targets at either -0.5m or +0.5m (see *Figure 15*).

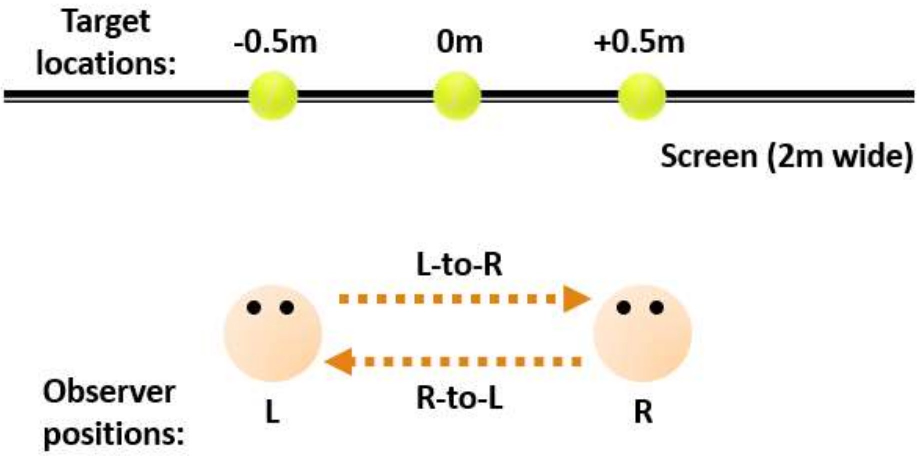


Figure 15: Exp 1 – Target locations and observer position diagram. From the top view.

In the static (S) conditions, participants stayed at the initial position after target presentation. In optic flow (OF) conditions, participants experienced one meter of visually-induced lateral movement from one observer position to another, L-to-R or R-to-L while the screen was filled with screen-stationary random dots (see *Figure 12C*). Translation duration was 7 seconds to provide sufficient time for the participant to experience visual motion. The scene was moved at velocity of 0.14 m/s, translated at constant velocity for 7 seconds, then rapidly decelerated at maximum capacity until it stopped using the same profile as illustrated in *Figure 9* for the physical motion profile.

The simulated screen in VR was 2m away from the viewing camera, i.e., the observer, to allow participants to view the whole screen while also being able to see some of the virtual environment. Therefore, the eccentricities of the targets were: 0m (0°), +0.5m (+14°), and +1m (+28°) when observer was at L, -1m (-28°), -0.5m (-14°), and 0m (0°) to the R (see *Figure 15*). In red-dot (RD) conditions, a red dot was displayed on a black wall 2m away from the observer in the direction participant was pointing during the response phase. In no-dot (ND) conditions, there was no visual feedback of where the participant was pointing.

3.3. Experimental Design

During the updating test, there were four distinct experimental blocks corresponding with two main factors (see Table 1). Factor A, visual motion: stationary (S) or optic flow (OF), and Factor B, presence of pointer during response phase: red dot (RD) or no dot (ND). The order of blocks was counter balanced to cover all possible combinations, and each participant was randomly assigned to a set order of blocks.

Table 1

Experimental conditions:	**With Red Dot (RD)**	**No Dot (ND)**
Stationary (O)	S-RD (Control)	S-ND
Visual Movement (OF)	OF-RD	OF-ND

For each block, there were three target locations. Factor C, eccentricity of the targets: 0m, .5m, and 1m. Factor D, the target side depended on the observer positions: right when the observer started at the left side of the display (L), right when the observer started at the right side (R).

Each block consisted of 5 trials for each target location at each observer position, comprising 30 trials (5 trials × 3 target locations × 2 observer positions) per block, which took about 20 minutes to complete, and each block was repeated four times, thus yielding 120 total trials per participant (~1 hour including breaks).

3.4. Tasks

Participant first performed the distance perception test (see section 2.5.1), and then received pointing training followed by the pointing test (see section 2.5.2). After they passed the pointing test, they did the updating test (section 2.5.3). See procedures section of the general methods for detailed procedure for each task.

3.5. Outliers

A total of 56 data points out of 1,680 (approx. 3.33%) were removed as outlying data points after the analysis (see section 2.6.1 for criteria). No participant was removed as an outlier in this experiment.

3.6. Results

3.6.1. Distance perception.

On average, the participants matched visual size of the reference ball was 25cm (100% larger than the actual reference ball size). Each participant's perceived distances to the screen was calculated using the formula shown in Figure 14, and the screen was perceived as 36% closer on average than the 2m as designed in the virtual environment. I looked at the correlation between the errors in perceived target distance and the remembered target eccentricity to access the effect of the perceived scale of the environment in our spatial coding (see *Figure 16*). The perceived distance errors and the remembered target eccentricity errors were not significantly correlated when static, $r = .262$, $p = .365$, but they were after visual lateral motion, $r = .548$, $p = .043$.

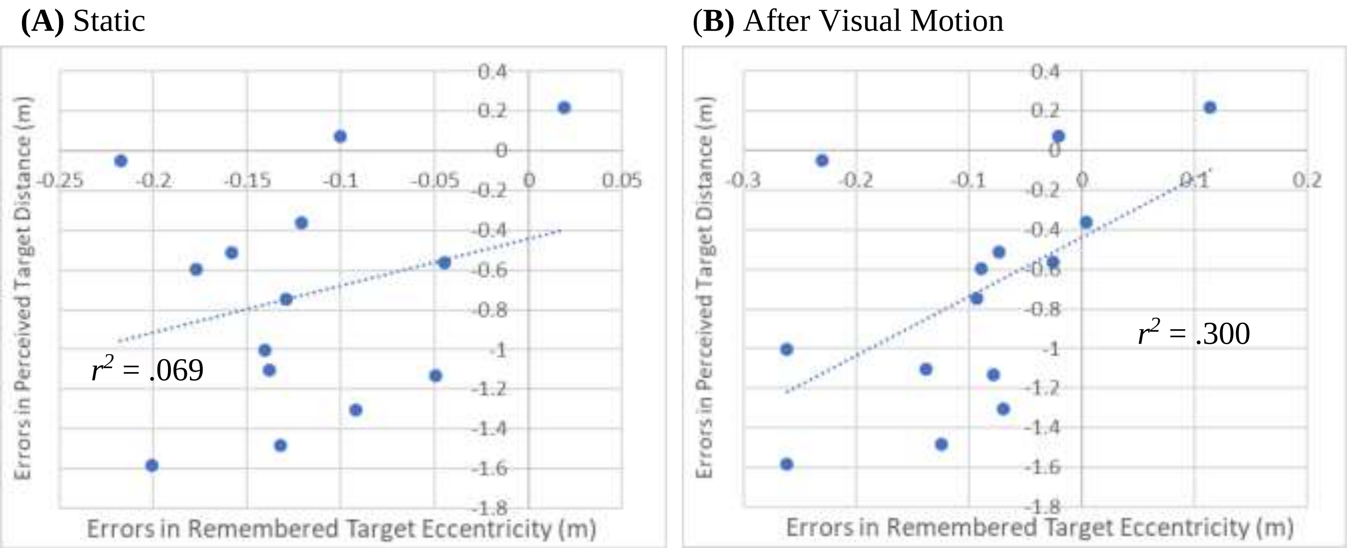


Figure 16: Exp 1 – Effect of perceived distance errors on remembered target eccentricity. Correlation between perceived target distance errors and remembered target eccentricity errors when (A) Static, and (B) After visually-induced lateral movement. Each dot represents average errors in remembered target eccentricity for a single participant (0 on x-axis represent actual target eccentricity).

3.6.2. Target eccentricity.

The pointing errors participants made as a function of eccentricity were compared using Linear Mixed Model repeated measures analysis. The analysis revealed a significant main effect of target eccentricity, *F* (2, 311) = 13.645, *p* < .001. On average, participants underestimated target eccentricity with greater errors for more eccentric targets. The mean errors were -.018m (*SD* = .209m) when the target was directly in front of them (at 0m eccentricity), -.057m (*SD* = .193m) for targets at 0.5m eccentricity, and -.160m (*SD* = .256m) for 1m eccentricity (average gain of .86, a value of 1 indicates perfect pointing at the target eccentricity). These data are shown in *Figure 17*.

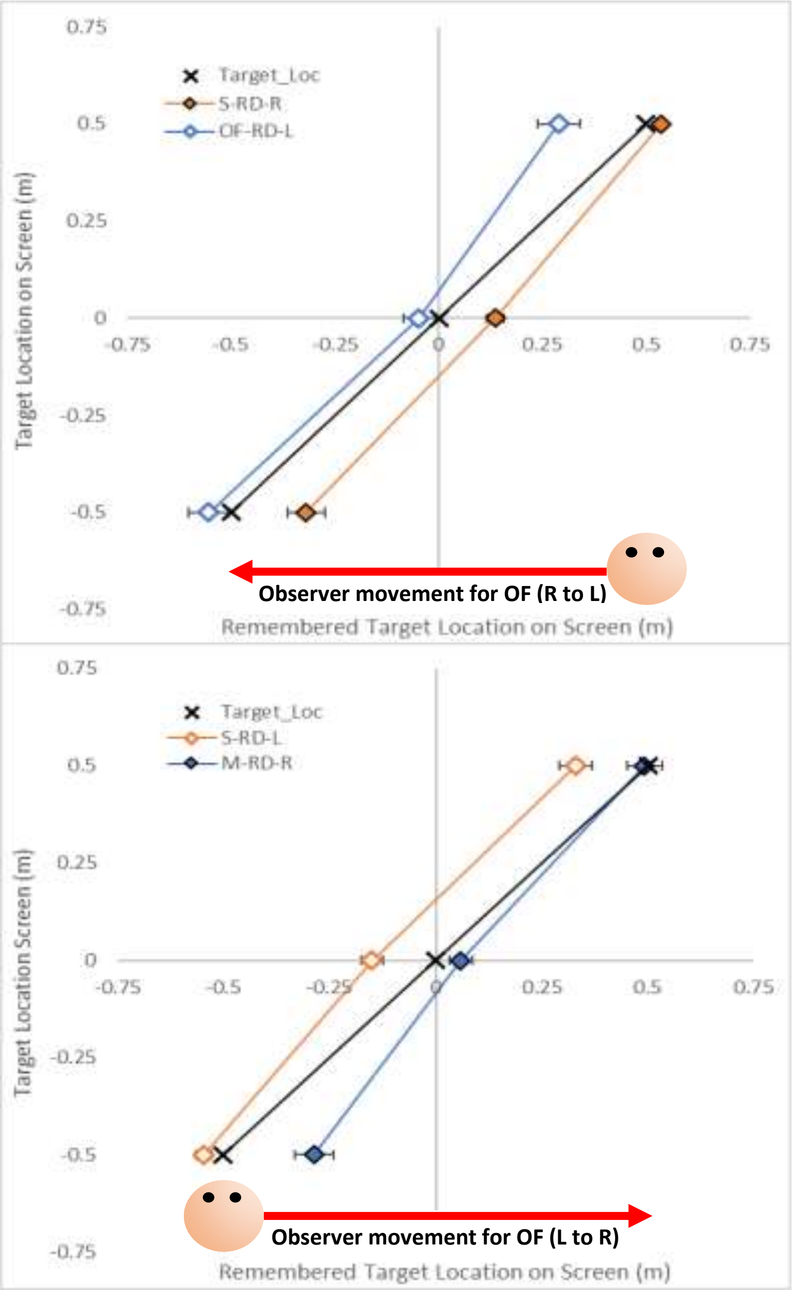


Figure 17: Exp 1 – Remembered target locations, from the center of screen (horizontal), before and after visually-induced movement: S – stationary, OF – visually-induced moving, L – observer at left, or moved to left, R – observer at right, or moved to right. X represent actual target locations on the screen. The error bars indicate the standard errors.

3.6.3. Comparing red-dot (RD) and no-dot conditions (ND).

The analysis revealed a significant main effect of the presence of the red-dot displayed at their pointing location, either displayed (RD) or not displayed (ND) during the response phase, *F* (1, 311) = 6.752, *p* = .010. Participants made greater errors when pointing at the target in RD conditions (*M* = .108, *SD* = .150) compared to the ND conditions (*M* = .049, *SD* = .283).

A significant interaction between the presence of red-dot and the observer position was also found, *F* (1, 311) = 4.423, *p* = .036. The post-hoc pairwise comparison showed that the magnitude of the errors made from the left side significantly differed from the errors made from the right side in ND conditions only. This effect is shown in *Figure 18*, where the errors can be seen to be biased towards the right in ND conditions when pointing to the targets on the right side (blue lines). This asymmetry in errors was not observed in RD conditions (orange lines).

Figure 18: Exp 1 – Pointing errors in remembered target locations for each target eccentricity: S – static, RD – red-dot, ND – no-dot displayed, L - Observer position at left, R - Observer position at right. (+ values are to the right, - values are to the left) The error bars indicate the standard errors.

3.6.4. Comparing between stationary and moving conditions.

In RD conditions, where participants could see their pointing location, the remembered target locations shifted in the direction of the movement after moving. The magnitudes of the remembered target location shift did not differ between moving left or right; mean shift was .216±.015m (*Figure 17*).

Participant position/moving direction.

Comparing the E_{TE} (see section 2.6.2) using Linear Mixed Model analysis, there was no significant effect of observer position (left or right), *F* (1, 149) = .317, *p* = .574, or the moving direction (left-to-right or right-to left), *F* (1, 65) = .316, *p* = .576. Therefore, I combined them by averaging the E_{TE}s between the left and right side (see section 2.6.2).

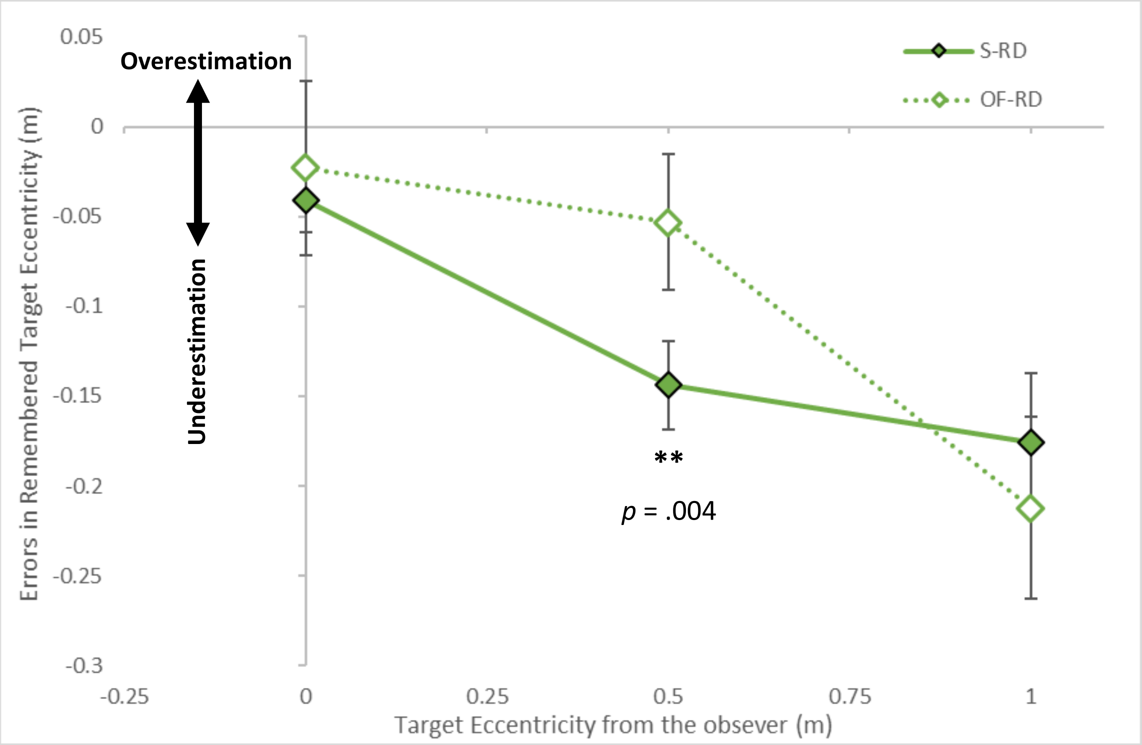


Figure 19: Exp 1 – Errors in remembered target eccentricity from the observer, at the time of pointing, for each target: S – stationary, OF – visually-induced moving, L – observer at left, or moved to left, R – observer at right, or moved to right. Errors were collapsed into errors to show the errors in target eccentricity. The error bars indicate the standard errors. Errors were compared between S and OF conditions for each target eccentricity at the time of the response phase (final eccentricity).

Analysis using the combined E_{TE}.

A Linear Mixed Model analysis comparing the combined E_{TE} between conditions revealed a significant interaction between movement condition and absolute target eccentricity, *F* (2, 143) = 4.334, *p* = .015. Further evaluation found a significant simple main effect of movement condition (between S and OF conditions) for targets at .5m eccentricity, *p* = .011 (after corrected using SDM), where the mean errors were -.144m for S conditions and -.053m for M conditions (see *Figure 19*).

3.6.5. Effect of visual movement

To evaluate the effect of visually-induced lateral movement, I compared the E_{DS}s (see Equation 1 in section 2.6.2) between each target eccentricity. Upon the analysis, I found a main

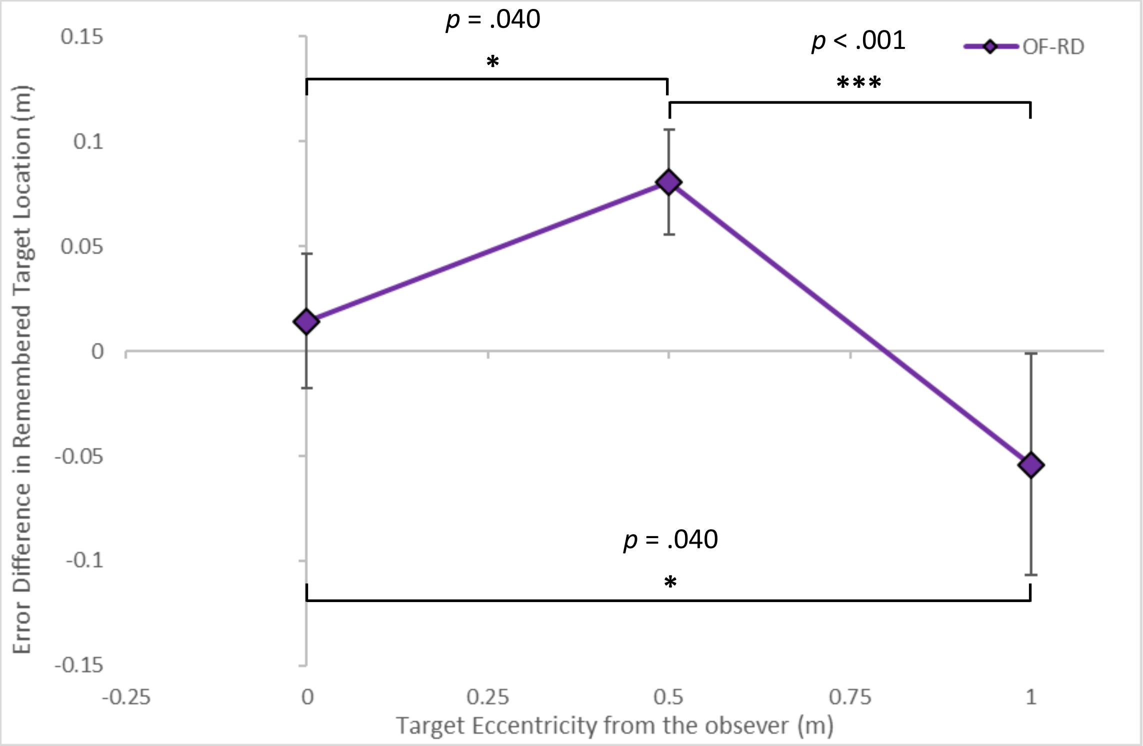


Figure 20: Exp 1 – Error differences between S and OF: Errors in remembered target location is subtracted from the errors made after visually-induced movement. (+ values indicate greater errors after movement, and - values indicate smaller errors after movement compared to static) The error bars indicate the standard errors.

effect of target eccentricity; $F(2, 65) = 9.083$, $p < .001$. Further evaluation of the main effect contrasts revealed that of these error differences were significantly different between each target eccentricity (*Figure 20*).

3.7. Discussion of Experiment 1

From the evaluation of pointing errors, the eccentricity of targets appears to be underestimated in general with the magnitude of the errors correlated with the target eccentricity. This result is not surprising based on the past studies that also showed underestimation of target eccentricity (Prablanc, Echallier, Komilis, & Jeannerod, 1979). However, past studies used a real environment and targets within arm's reach. My current experiment shows that the underestimation effect extends to the virtual environment and at distances beyond where participants could physically reach.

When people cannot see where they are pointing, they must rely on proprioceptive senses (and efferent copy) to determine the position of their hand and hence their pointing location. When participants could not see where they were pointing, the underestimation was reduced for targets on the right side. However, this may simply be the result of a rightwards, or outwards, bias due to using their right hand to point at the targets on the right side. Nonetheless, these asymmetric errors between the left and right targets may affect people's pointing performance in undesirable ways. For this reason, I did not use their responses obtained without a pointer to analyze the effect of self-motion.

Looking at the correlation between the participant perceived distance and their remembered target eccentricity errors (see *Figure 16B*) revealed that the closer participants perceived the virtual screen on which the targets were presented, the less eccentric they remembered targets after moving. This finding is the opposite of the hypothesis I made in section

1.5 (hypothesis #4). Shorter perceived distance is associated with slower perceived velocity (Wist, Diener, Dichgans, & Brandt, 1975). Based on the prediction presented in section 1.3, underestimated target eccentricity after moving would be associated with underestimated travel distance. It is possible that participants underestimated the distance they traveled due to the underestimated speed, resulting in the underestimated target eccentricity after moving (see *Figure 4*).

After visually-induced lateral motion, the remembered target locations shifted (approximately 21.6% of the visually simulated self-motion on average) in the direction of movement (the moving direction, left or right, did not matter) confirming previous studies (Klier et al., 2008). There are two possible source for this shift: a) underestimation of movement distances (as shown on *Figure 4* in section 1.3) which bring the remembered targets towards their movement direction, or b) underestimation of the target eccentricities after visually-induced lateral movement at the final observer position. If the remembered target locations were only affected by target eccentricity, and the visually-induced movement had no influence, the errors people made for the target of same eccentricity when static and after movement would be the same. For the targets at 0m and 1.0m eccentricities, people made identical errors whether they were static or after the visually-induced movement (see *Figure 19*). However, people made smaller errors after the movement for targets at .5m eccentricity, the target between the initial and final observer locations, compared to static. These results suggest that updating may be affected by the target eccentricity rather than the movement per se, and the only targets affected by movement may be targets within the range of movement. With three targets, however, only one target fell within the range of movement and the rest were at the start and end of movement which may not be enough targets to make a solid conclusion of the effect of visually-induced lateral motion when updating targets in front. Therefore, I conducted experiment 2 with additional targets spread over a larger range.

4.0. Experiment 2

In the experiment 1, there was only one target that fell within the range of motion (at .5m eccentricity) and it was only that target that showed a significant reduction in underestimation of target eccentricity after moving. To expand on this finding, the number of targets was increased to seven in this experiment: one at the initial, one at the final position, three within the range of motion, and two outside the range of motion. Because the performance without pointer feedback during response phase was deemed to be unreliable and showed a bias towards the right, I used the red dot (RD) during the response phase in all conditions for this experiment.

4.1. Participants

Fourteen females and six males (20 total), average age of 20.55 years (*SD* = 3.72), participated in the study. Participants were recruited via York University's Undergraduate Research Participation Pool (URPP) and given course credit. All participants had normal or corrected-to-normal vision and were right handed. All the participants gave informed consent. The experiment was approved by the York University's Ethics Review Board and was carried out using the principles of the Treaty of Helsinki.

4.2. Stimuli

The virtual environment and visually induced self-motion in experiment 2 were identical to experiment 1, except there were seven targets. Targets were spread out horizontally at 0.75m, -0.5m, -0.25m, 0m, +0.25m, +0.5m, and +0.75m away from the center of the screen, with two observer positions – left (L) and right (R) in front of the targets at -0.5m and +0.5m (see *Figure 21*).

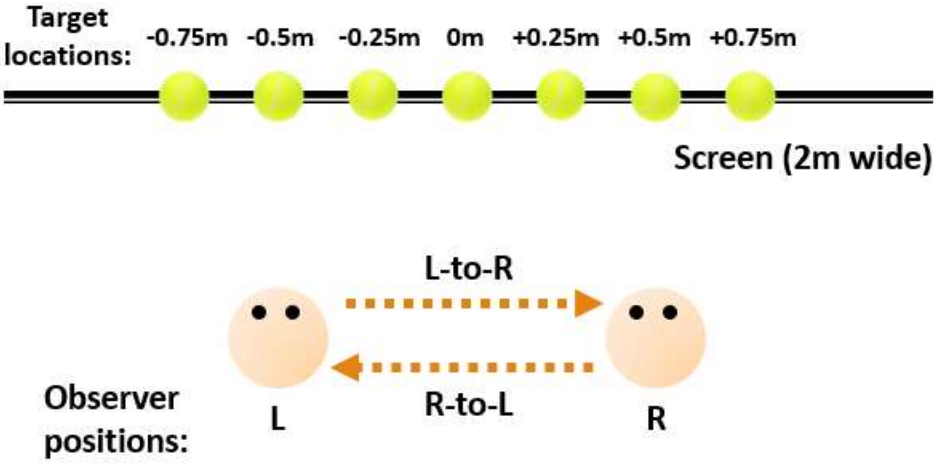


Figure 21: Exp 2 – Target locations and observer position diagram. From the top view.

The simulated screen in VR was 2m away from the viewing camera, as in experiment 1. Therefore, the eccentricities of the targets were: -0.25m (-7°), 0m (0°), +0.25m (+7°), +0.5m (+14°), +0.75m (+21°), +1m (+28°), and +1.25m (+35°) when the observer was at L, -1.25m (-35°), -1m (-28°), -0.75m (-21°), -0.5m (-14°), -0.25m (-7°), 0m (0°), and +0.25m (+7°) at R. The red dot was displayed on a flat black surface 2m away from the observer, the same distance as the screen, in the direction the participant was pointing during the response phase.

Identical to experiment 1, participants stayed at their initial position after target presentation in static (S) conditions. In optic flow (OF) conditions, participants experienced one meter of visually-induced lateral movement from one observer post to the other, L-to-R or R-to-L. Motion was visually induced by moving the scene in front of them including the projection screen filled with screen-stationary random dots. The translation duration was 7 seconds at a constant velocity of .14 m/s as before.

4.3. Experimental Design

During the updating test there were two distinct experimental blocks corresponding with the main factor. Factor A, visual motion: stationary (S) or visually induced lateral motion by optic flow (OF). Each block was conducted twice (2 blocks for S and 2 blocks for OF; 4 blocks total), the order of blocks was counterbalanced to cover all possible combinations, and each participant was randomly assigned to a set order of blocks. For each block, there were seven target eccentricities. Factor B, eccentricity of the targets: -0.25m, 0m, +0.25m, +0.5m, and +0.75m. Factor C, the target side depended on the observer position: right when the observer started at the left (L), and right when the observer started at the right (R). Each block consisted of 2 trials for each target location at each observer position, comprising 28 trials (2 trials × 7 target locations × 2 observer positions) per block, which took about 15 minutes to complete, thus there were 56 trials per condition (28 trials × 2 blocks) and 112 total trials per participant (~1 hour including breaks).

4.4. Task

All the tasks for exp 1 were identical to exp 1 except there was no ND condition, without red-dot displayed at the participant pointing location during response phase. However, participants were instructed to keep their right hand, with the controller, on top of their right leg at the start of each trial and kept it there until they had to point at the target location (after the second bell). This ensured that all pointing movements started from the same place.

4.5. Outliers

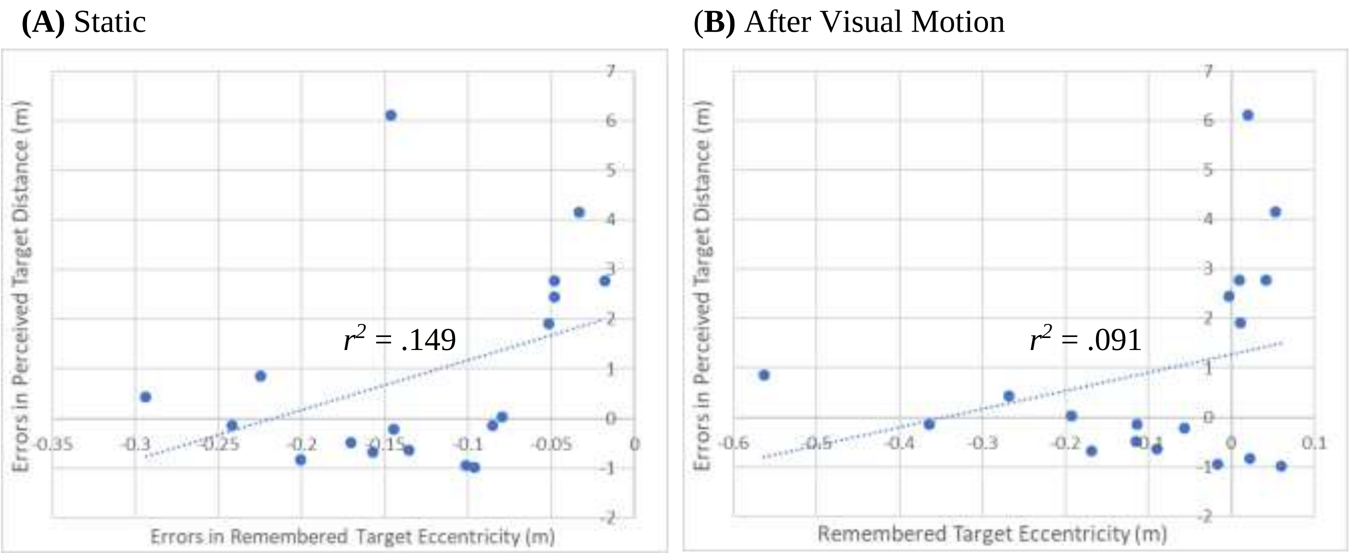
Total of 53 data points out of 2,255 (approx. 2.35%) were removed as outlying data points after the analysis (see section 2.6.1 for criteria). No participant was removed as an outlier in this experiment.

4.6. Results

4.6.1. Distance perception.

Distance perception test data from one participant was missing due to an issue with the test program. With the remaining nineteen participants, the average of the visual size matched for the reference ball was 12.4cm (4.9% smaller than the actual size). Each participant's perceived size was converted to perceived distance (using the formula in Figure 14). After the conversion, another participant was removed as an outlier (see section 2.6.1 for criteria), leaving total of eighteen participants for the analysis.

Participants overestimated the screen distance by 45.6% (2.91m rather than the 2m as designed in the virtual environment). The range of perceived distance errors were 7.08m (perceived screen distances were between 1.02m and 8.10m). I looked at the correlation between the errors in perceived target distance and the remembered target eccentricity to access the effect of the perceived scale of the environment in our spatial coding (see *Figure 22*). The perceived distance errors and the remembered target eccentricity errors were not significantly correlated either when static, $r = .387$, $p = .113$, or after visual lateral motion, $r = .302$, $p = .223$.


(A) Static

(B) After Visual Motion

Figure 22: Exp 2 – Effect of perceived distance errors on remembered target eccentricity. Correlation between perceived target distance error and remembered target eccentricity when (A) Static, and (B) After visually-induced lateral movement. Each dot represents average errors in remembered target eccentricity for a single participant (0 on x-axis represent actual target eccentricity).

4.6.2. Target eccentricity.

The pointing errors participants made, in terms of target eccentricity from the observer, were evaluated using a linear mixed model repeated measures analysis. The analysis revealed a significant main effect of target eccentricity, *F* (6, 513) = 63.894, *p* < .001. On average, participants underestimated target eccentricity with greater errors for more eccentric targets.

4.6.3. Comparing between stationary and moving conditions.

Linear Mixed Model analysis, using a random intercept model, revealed significant main effect of visually-induced motion, *F* (1, 513) = 12.125, *p* = .001. On average, pointing errors were greater in S conditions (*M* = .125, *SD* = .146) compared to OF conditions (*M* = .081, *SD* = .247).

A comparison of the static data (blue lines) and the after-movement data (orange line) shows that remembered target locations were shifted after moving in the direction of the movement (see *Figure 23*). The magnitude of shift did not differ between the two directions of motion; mean shift was .201±.015m.

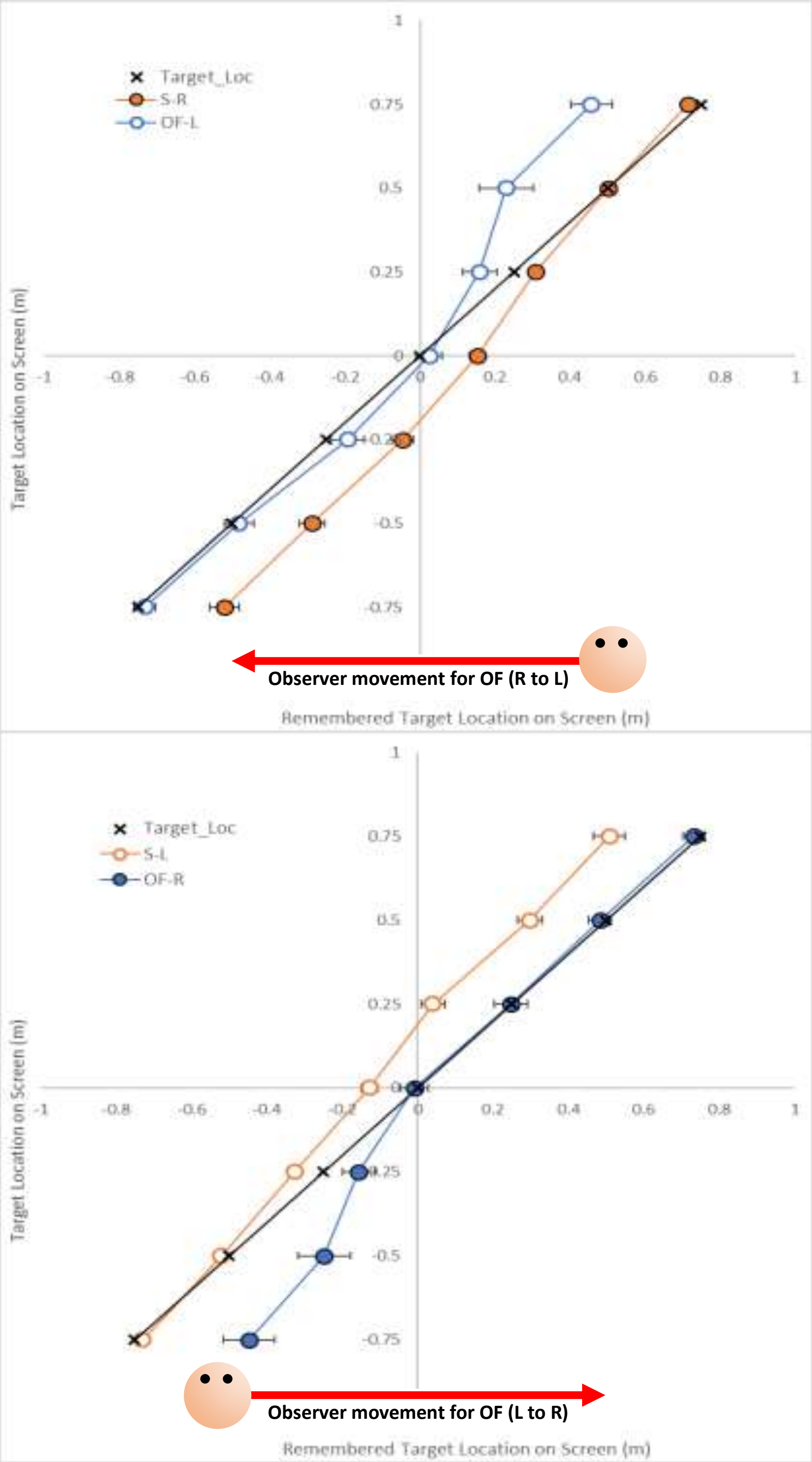


Figure 23: Exp 2 – Remembered target locations, from the center of screen (horizontal), before and after visually-induced movement: S – stationary, OF – visually-induced moving, L – observer at left, or moved to left, R – observer at right, or moved to right. X represent actual target locations on the screen. The lines were fitted using quadratic function. The error bars indicate the standard errors.

Participant position/moving direction.

I averaged E_{TE}s between the left and right side collapsing them into the same side (see section 2.6.2), because Linear Mixed Model analysis did not reveal any significant difference between observer positions, *F* (1, 527) = .046, *p* = .831, or the moving directions, *F* (1, 247) = .329, *p* = .567.

A significant interaction between visually-induced motion and target eccentricity was found, *F* = 8.651, *p* < .001. Evaluation of simple main effect showed that the errors were significantly different between S and M conditions for targets at +.25m (*p* = .001), +.5m (*p* < .001), +.75m (*p* < .001), and +1.25m eccentricity (*p* = .032), see *Figure 24*.

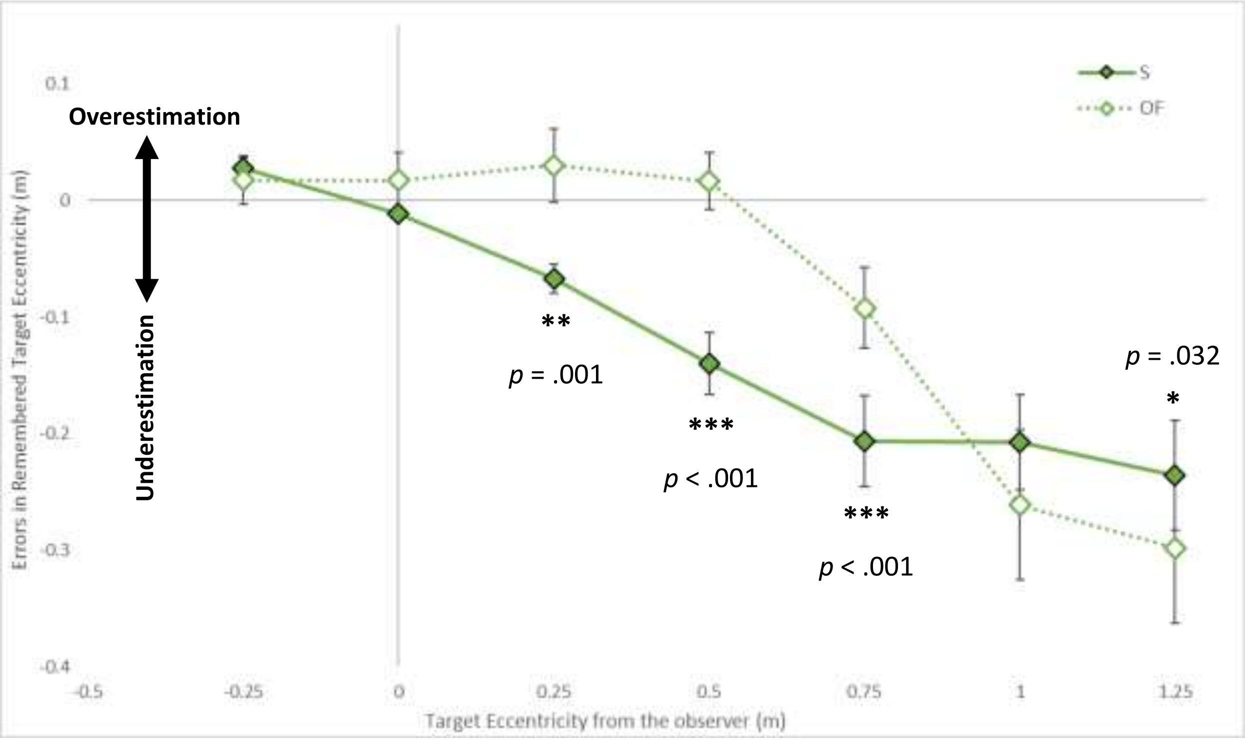


Figure 24: Exp 2 – Errors in remembered target eccentricity for each target (observer at 0 at the time of pointing): S – static, OF – visually-induced moving, L – observer at left, or moved to left, R – observer at right, or moved to right. (+ values are overestimation, - values are underestimation) The error bars indicate the standard errors. Errors for each target eccentricity at the time of the response phase (final eccentricity) were compared between S and OF conditions.

4.6.3. Effect of the visual movement

Upon comparing the E_Ds to evaluate the effect of visually-induced lateral movement (see section 3.6.5), I found a main effect of target eccentricity; *F* (6, 247) = 15.334, *p* < .001. Further evaluation of the main effect contrasts revealed that the error differences were only significantly different between 0m and .25m (*p* = .013), and .75m and 1m (*p* < .001) eccentricity (see *Figure 25*).

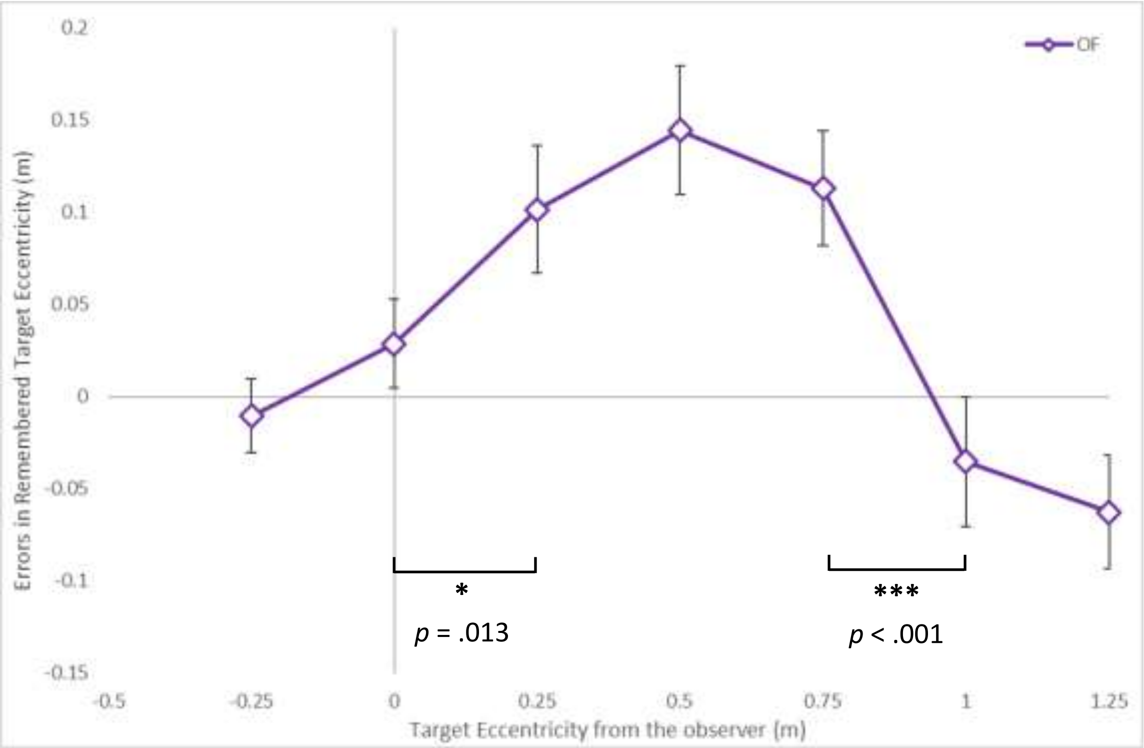


Figure 25: Exp 2 – Error differences between S and OF: Errors in remembered target location is subtracted from the errors made after visually-induced movement. (+ values indicate greater errors after movement, - values indicate smaller errors after movement) The error bars indicate the standard errors.

4.7. Discussion of Experiment 2

Participants again underestimated target eccentricity with the magnitude of the errors correlating with the real target eccentricity (average gain of .81). Remembered target locations were again shifted (approximately 20.1% of the visual movement on average) in the direction of movement after visually-induced lateral motion. The magnitude of shift varied depending on the target eccentricity. The errors made for targets within the range of movement (targets at .25m, .5m, and .75m eccentricity) were different between when pointing at them after being stationary and after moving, a phenomenon which was also found in experiment 1. In fact, the participants became more accurate for those targets after they moved which suggest either a) moving (i.e., the updating process) enhances the memory of the locations, or b) moving cancels out the errors people made when static (possibly with additional errors). This finding suggests our updating may indeed depends on the range of motion.

Unlike in the experiment 1, there was no significant correlation found between the participant perceived distance and their remembered target eccentricity errors despite the similar trend shown in the graphs (see *Figure 22*). However, the distance perception test performance of some participants showed questionable results with very large errors (up to 305%). Binocular vision is important for depth perception (Allison, Gillam, & Vecellio, 2009). Some participants may have had trouble with stereopsis, resulting in large error in perceived distance. I added a stereotest as a new screening procedure in the experiment 3 to ensure participants can correctly use stereopsis for perceiving depth when using the VR HMD.

So far, in experiment 1 and 2, all the movements have been visually simulated (vection). In the real world, people need to perform updating during physical motions. Physical motions, as described in the introduction, involves other sensory cues such as the vestibular and somatosensory cues as well as expectancies brought about by the efference copy of any intended movement. To look at the at the contribution of these additional sensory information, but without efference copy, in experiment 3 I introduced passive physical movement and compared the results with the visual-only results I have presented thus far.

5.0. Experiment 3

The experiment 1 and 2 showed that people make errors when pointing at targets even when static and these errors increased for more eccentric targets. These errors were reduced after visually lateral translation, but only for the targets that were within the range of the movement. In experiment 3, I added physical motion to the movement phase using the MMS to evaluate the contribution of physical motion cues to this phenomenon. The test room (with MMS) was identical to the virtual test environment to provide a familiar natural scene in VR. I also added stereotest as a new screening procedure to ensure participants can correctly perceive depth in the real test room and in the virtual test room using the stereo display on the VR HMD.

Originally, the experiment was planned to be conducted in both the real and the virtual test room. However, due to a technical difficulty in using Oculus Touch as a pointing device, test was only conducted in the virtual environment.

5.1. Subject screening

Participants were tested for stereopsis before participating in the study using RANDOT® Stereotests, by Stereo Optical Company, Inc. They had to score 5 or higher out of 10 (70 seconds of arc at 16 in.) to participate. One out of 30 total participant (3.33%) was deemed not suitable to partake in the study for scoring less than 5.

After the stereotest, participants went through pointing training (section 2.5.2). One out of 29 total participant (3.45%) who partook in training could not pass and was removed from the study.

5.2. Participants

Twenty-eight undergraduate students participated in the study after passing the screening. Two participants were removed from the study due to errors found in the software used during testing, and two participants did not finish the test. After the removal of these four participants, I ended up with fourteen females and ten males (24 total), average age of 20.75 years (*SD* = 3.98), in the study. Participants were recruited via York University's Undergraduate Research Participation Pool (URPP) for course credit. All participants had normal or corrected-to-normal vision and were right-handed. All the participants gave informed consent. The experiment was approved by the York University's Ethics Review Board and was carried out using the principles of the Treaty of Helsinki.

5.3. Stimuli

The virtual environment and visually-induced self-motion were identical to those used in experiment 2, except that the number of targets viewed from each starting position was reduced to four to keep test time to under 2 hours. The simulated screen in VR was 1.75m away from the viewing camera, i.e., the observer, to mimic the MMS room. Thus, the eccentricities of the targets were: -0.23m (-7.5°), 0m (0°), +0.23m (+7.5°), and +0.46m (+15°) when the observer was at L, -0.46m (-15°), -0.23m (-7.5°), 0m (0°), and +0.23m (+7.5°) at R displayed on a simulated screen at 1.75m away from the observer (see *Figure 26*). During the response phase, the red dot was displayed on a black wall at the same distance, in the direction participant was pointing.

5.4. Experimental Design

After the target was presented in each trial of the updating test, participants were either 1) stationary (S), 2) physically moved by the MMS with the HMD screen on showing motion consistent with the physical motion (M), 3) visually moved with the HMD screen showing the optic flow of the scene (OF), or 4) physically moved by the MMS with a dark screen on the HMD (P). Each participant completed four test blocks – S, M, OF, and P. The order of blocks

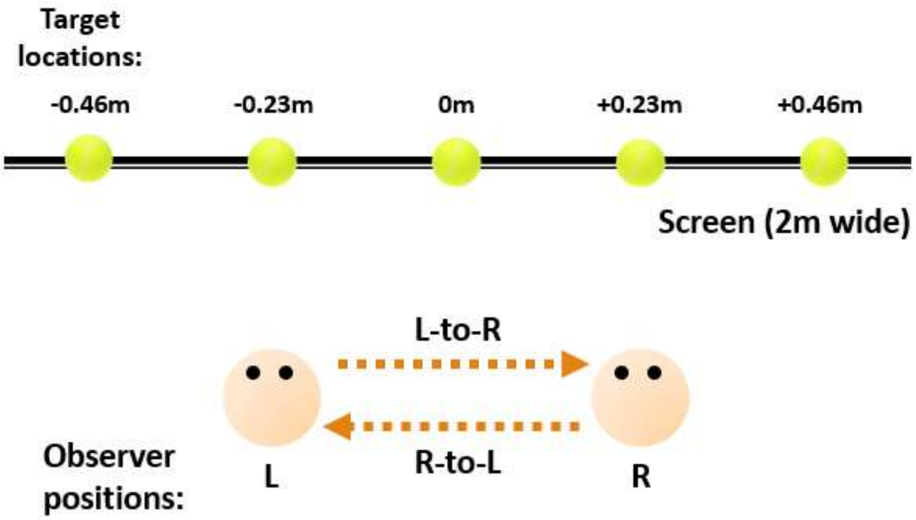


Figure 26: Exp 3 – Target locations and observer position diagram. From the top view.

was randomized to counterbalance any possible order effect. For all moving conditions (M, OF, and P), participant either moved from the left-to-right, or right-to-left depending on their initial observer position.

For each block, there were five target eccentricities – spread horizontally at -0.23m, 0m, +0.23m, +0.46m, and +.69m from the observer, with two observer positions – left (L) and right (R) in front of the targets at -0.23m and +0.23m. One block consisted of 4 trials for each target location at each observer position, comprising 40 trials (4 trials × 5 target locations × 2 observer positions) per block, which took about 20 minutes to complete, thus 160 total trials per participant (~1.5 hours including breaks).

5.5. Task

All the tasks for exp 3 were the same as in exp 2.

5.6. Outliers

Total of 131 data points out of 3,848 (approx. 3.40%) were removed as outlying data points after the analysis. One participant was removed as an outlier in this experiment resulting in final analysis using responses from twenty-three participants.

5.7. Results

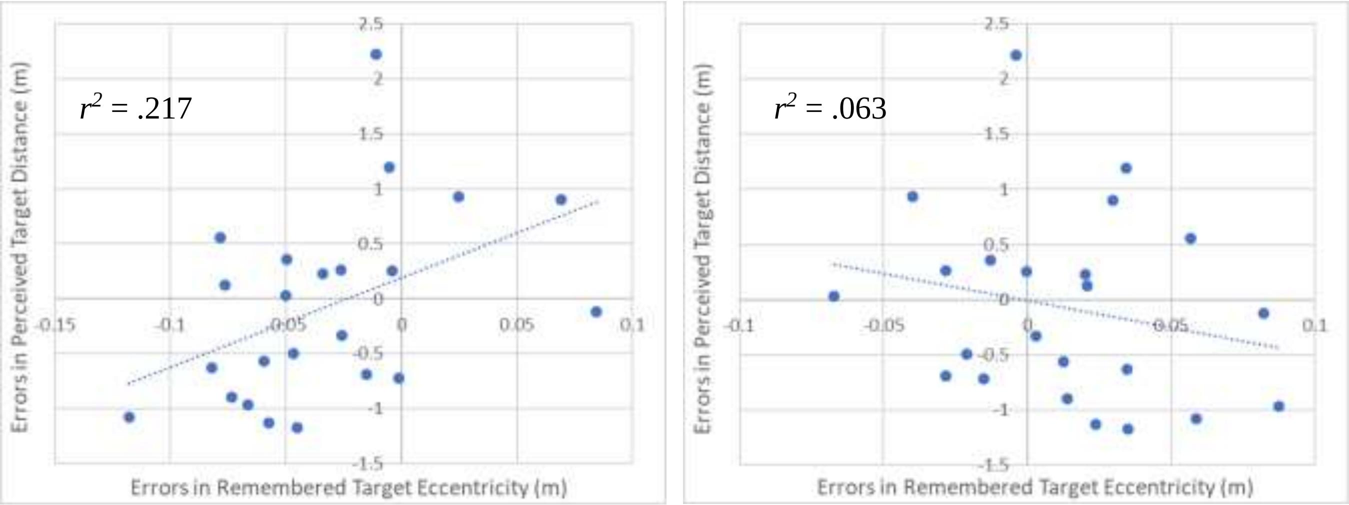
5.7.1. Distance perception.

On average, participants matched the visual size of the reference ball to 19.4cm (55.2% larger than the actual size) When each participant's perceived size was converted to the perceived distance (using the formula in Figure 14), the average underestimation of the screen distance was found to be 16.25% (1.47m rather than the 1.75m as designed in the virtual environment). I looked at the correlation between the errors in perceived target distance and the remembered target eccentricity to access the effect of the perceived scale of the environment (see *Figure 27*). The perceived distance errors and the remembered target eccentricity errors were significantly correlated when static, $r = .451$, $p = .031$, but not after passively moved laterally with both visual and physical cues, $r = -.218$, $p = .317$, visual cues only, $r = .037$, $p = .867$, or physical cues only, $r = -.122$, $p = .578$.

5.7.2. Target eccentricity.

The pointing errors participants made, in terms of eccentricity from the observer, were evaluated using a linear mixed model repeated measures analysis. The analysis revealed a significant main effect of target eccentricity, $F(4, 858) = 59.400$, $p < .001$. On average, participants underestimated target eccentricity with greater errors for more eccentric targets (The average gain of remembered target location when static was .81).

(A) Static **(B)** After Full Motion (Visual + Physical)



(C) After Visual Only Motion **(D)** After Physical Only Motion

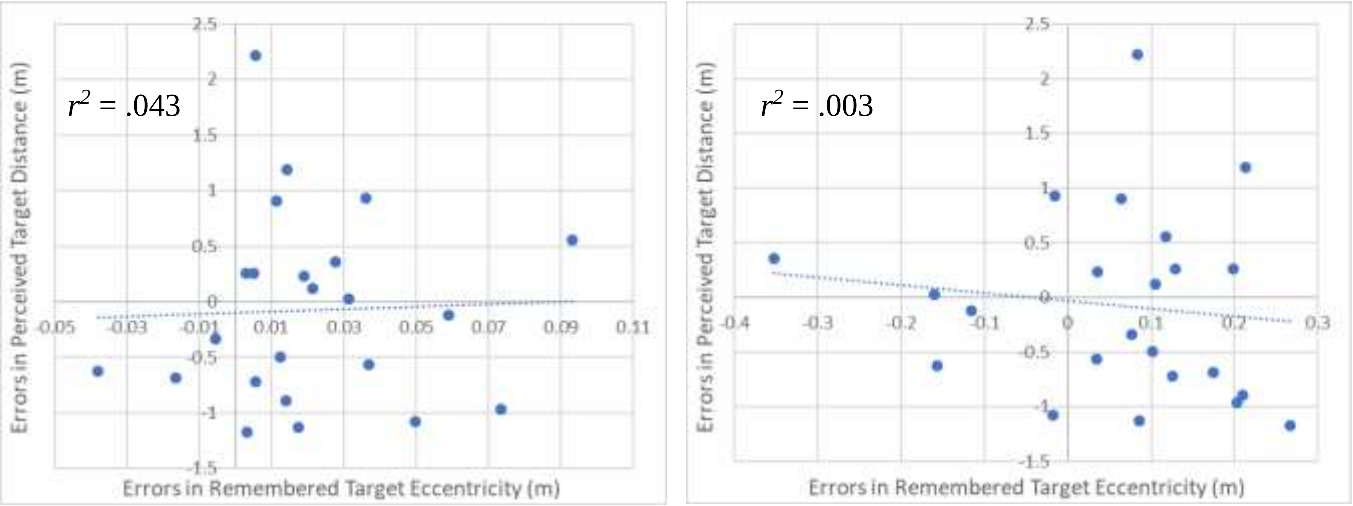


Figure 27: Exp 3 – Effect of perceived distance errors on remembered target eccentricity. Correlation between perceived target distance error and remembered target eccentricity when (A) Static, (B) After full (visual and physical cues) lateral movement, (C) After visual only movement, and (D) After physical only movement. Each dot represents average errors in remembered target eccentricity for a single participant (0 on x-axis represent actual target eccentricity).

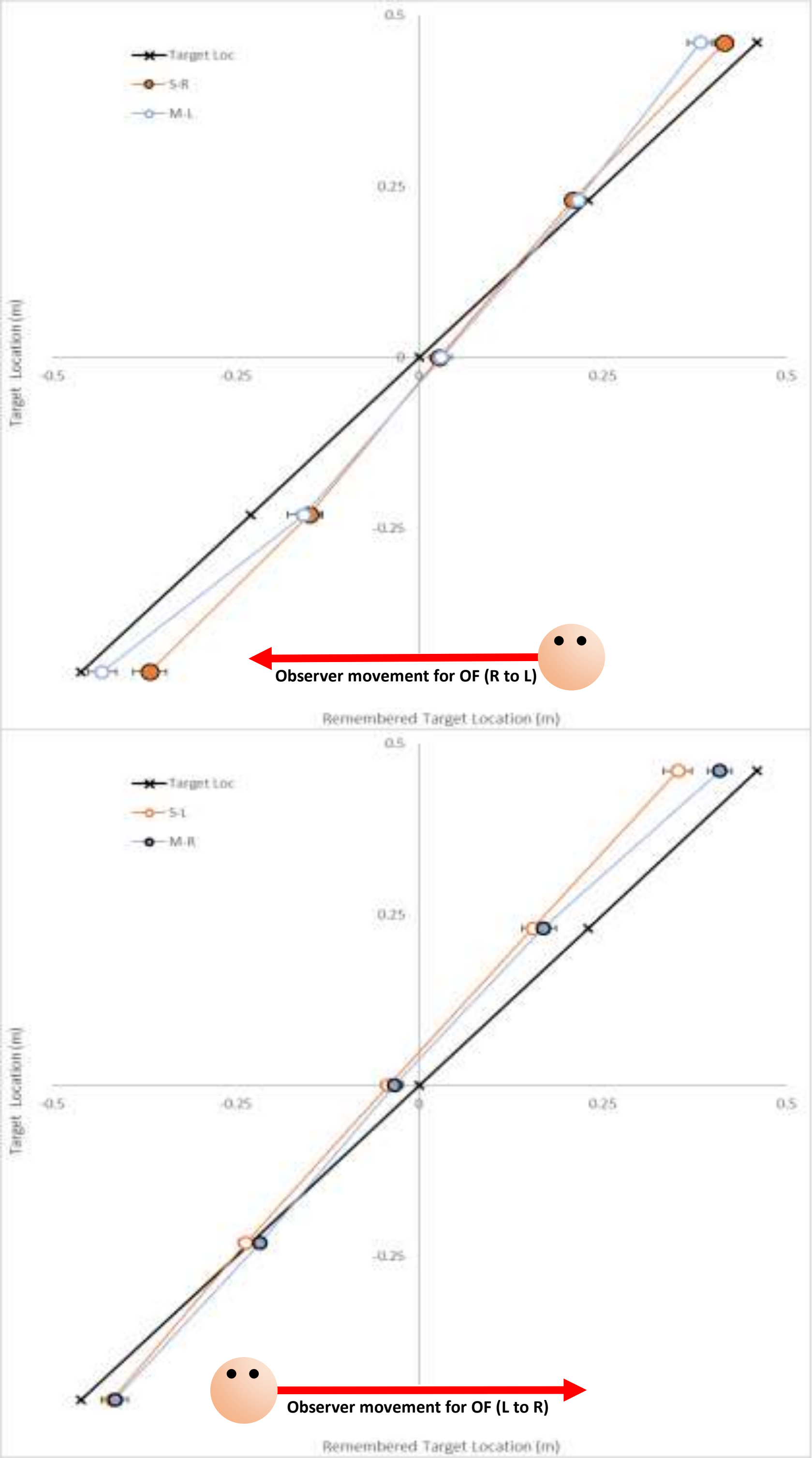


Figure 28: Exp 3 – Remembered target locations, from the center of screen (horizontal), before and after passive movement: S – stationary, M – full movement, L – observer at left, or moved to left, R – observer at right, or moved to right. X represent actual target locations on the screen. The error bars indicate the standard errors.

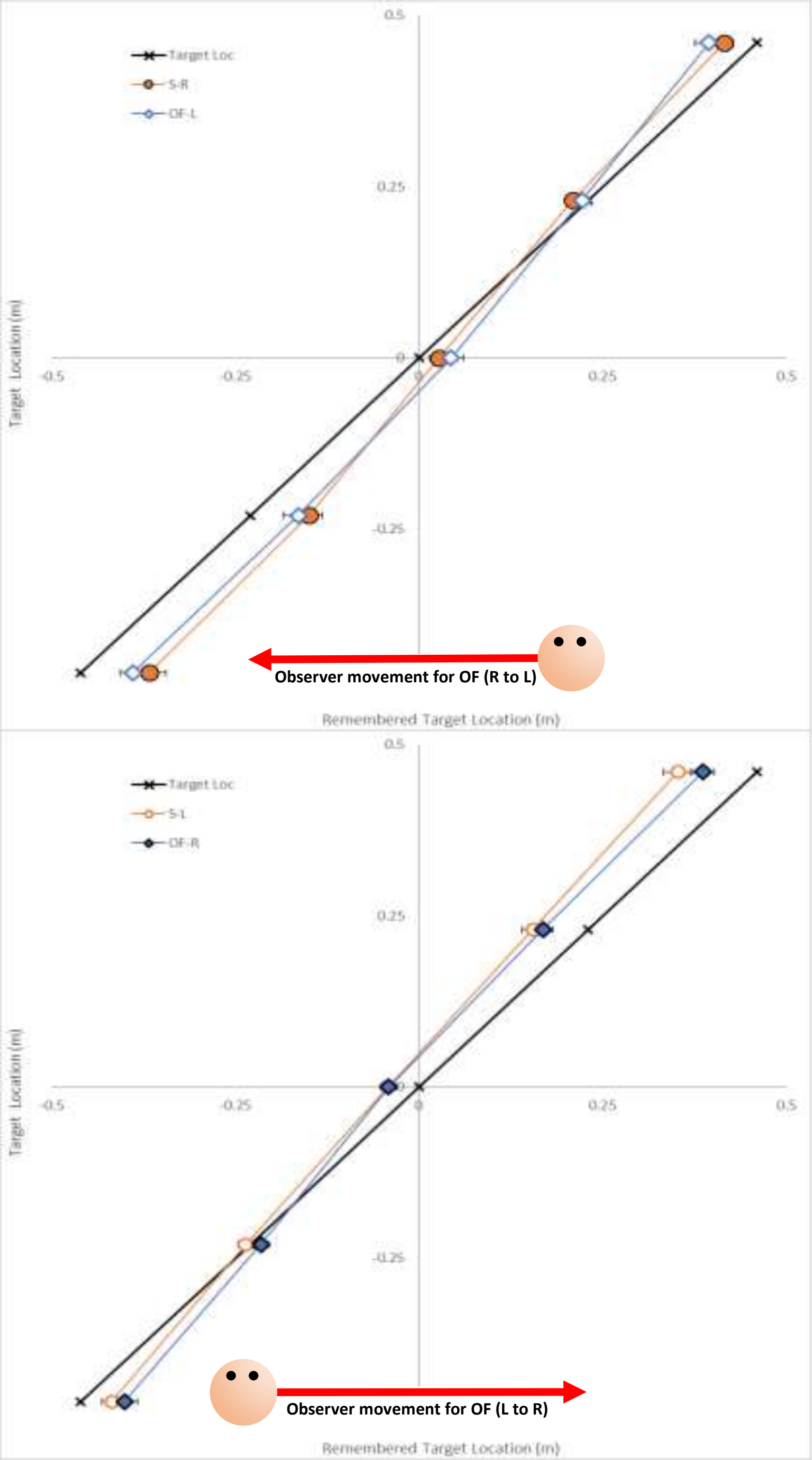


Figure 29: Exp 3 – Remembered target locations, from the center of screen (horizontal), before and after visually-induced movement: S – stationary, OF – visually-induced movement only, L – observer at left, or moved to left, R – observer at right, or moved to right. X represent actual target locations on the screen. The error bars indicate the standard errors.

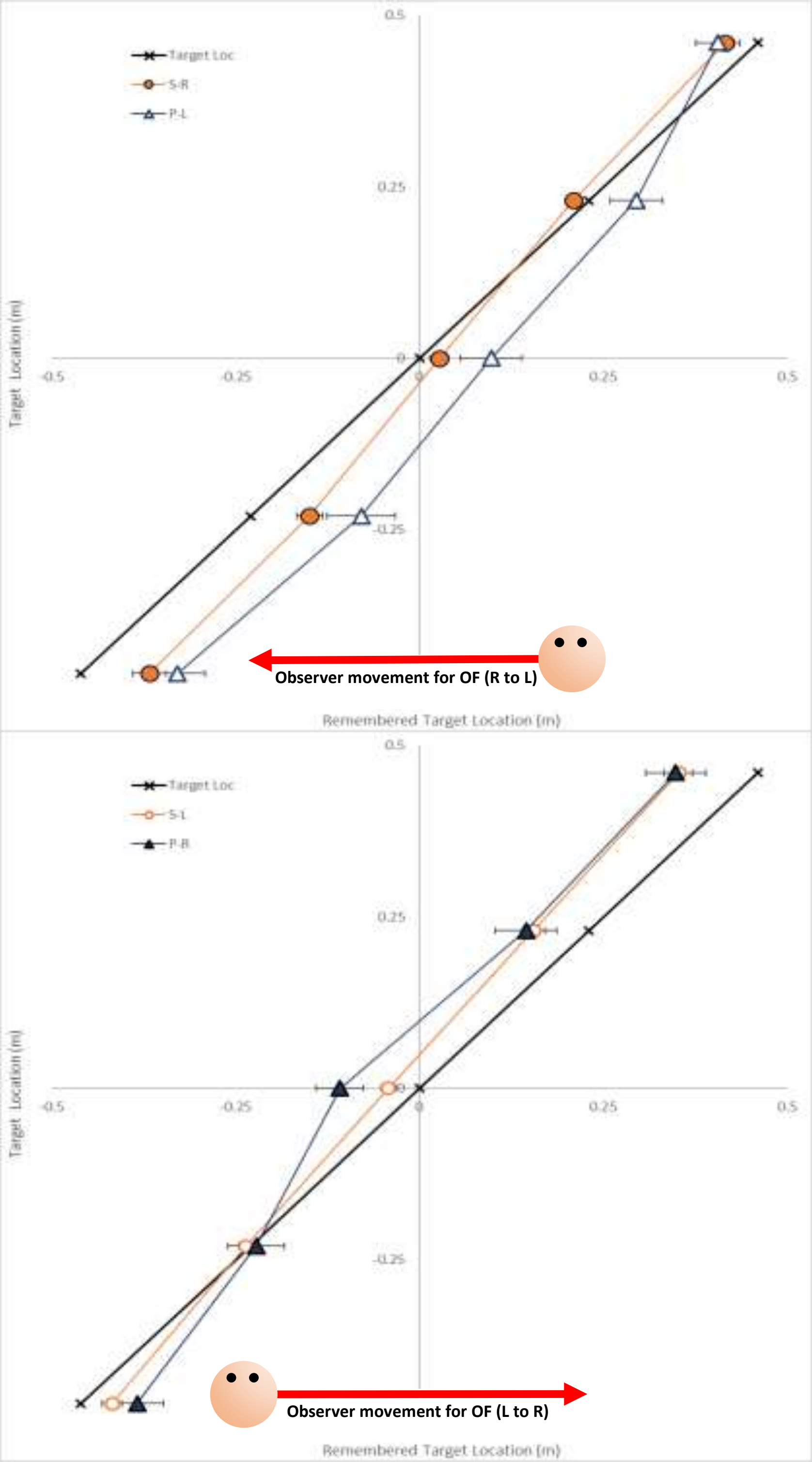


Figure 30: Exp 3 – Remembered target locations, from the center of screen (horizontal), before and after passive movement: S – stationary, P – physical movement only, L – observer at left, or moved to left, R – observer at right, or moved to right. X represent actual target locations on the screen. The error bars indicate the standard errors.

5.7.3. Comparing between movement conditions.

Remembered target locations were shifted in the direction of the movement after moving for the targets for conditions M (*M* = .020, *SD* = .025) and OF (*M* = .017, *SD* = .016); see *Figure 28* and *Figure 29*. However, the shift was in the opposite direction to the movement for the physical movement in the dark (P) condition (*M* = .029, *SD* = .043); see *Figure 30*. Participants had the least errors for the targets at 0m eccentricity at the initial position; the mean of the E_{TE} for these targets were .001m where the overall average E_{TE} was .032m.

Participant position/moving direction.

There was no significant difference found between the observer positions (left or right), *F* (1, 858) = .296, *p* = .586, or the moving directions (left-to-right or right-to left), *F* (1, 638) = 1.002, *p* = .317, after the Linear Mixed Model analysis of the E_{TE}. Therefore, the E_{TE}s were combined by averaging the left and right side (see section 2.6.2).

Analysis using the combined E_{TE}.

Further analysis using the combined E_{TE} revealed a main effect of movement, *F* (3, 858) = 30.076, *p* < .001. Target eccentricities were significantly more overestimated after movements compared to their estimated positions after the S condition: mean differences were .045m for M (*p* < .001), .053m for OF (*p* < .001), and .093m for P (*p* < .001) conditions (see *Figure 31*).

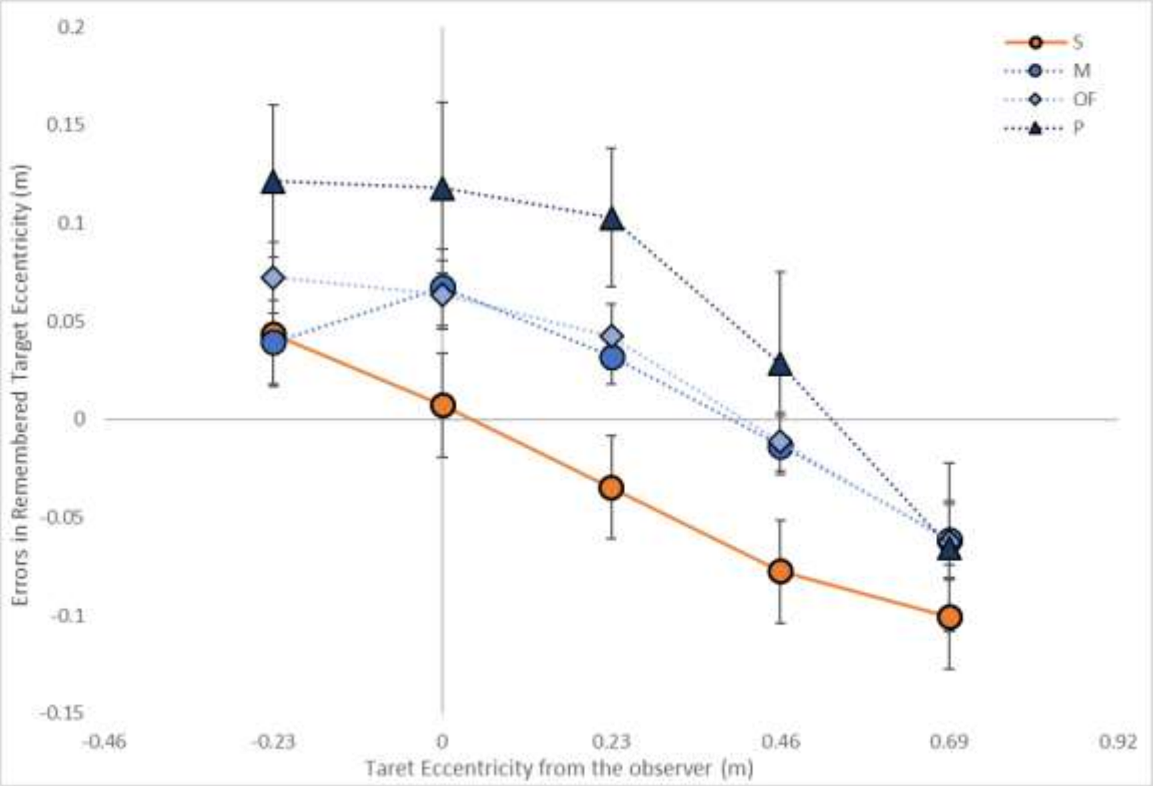


Figure 31: Exp 3 - Errors in remembered target eccentricity for each target (observer at 0 at the time of pointing): S – static, M – full movement, OF – visually-induced moving, P – physical movement only, L – observer at left when responding, R – observer at right when responding. (+ values are overestimation, - values are underestimation) The error bars indicate the standard errors. Errors were compared between S, M, OF and P conditions for each target eccentricity at the time of the response phase (final eccentricity).

5.7.4. Effect of the movements

To evaluate the effect of each movement, I compared the E_Ds between the movement conditions. Linear mixed-model analysis revealed that there was a significant main effect of movement conditions, F (2, 638) = 12.087, $p < .001$. The largest error differences were found in the physical-only (P) condition ($M = .093$, $SD = .195$), then visual-only (OF) condition ($M = .054$, $SD = .083$), and the full-motion condition (M) had the least differences ($M = .045$, $SD = .086$) (see *Figure 32*). Further evaluation of the main effect revealed that E_D in P conditions significantly differed from both OF (*p* < .001) and M (*p* < .001) conditions, but E_D of OF and M conditions did not significantly differ from each other (*p* = .405).

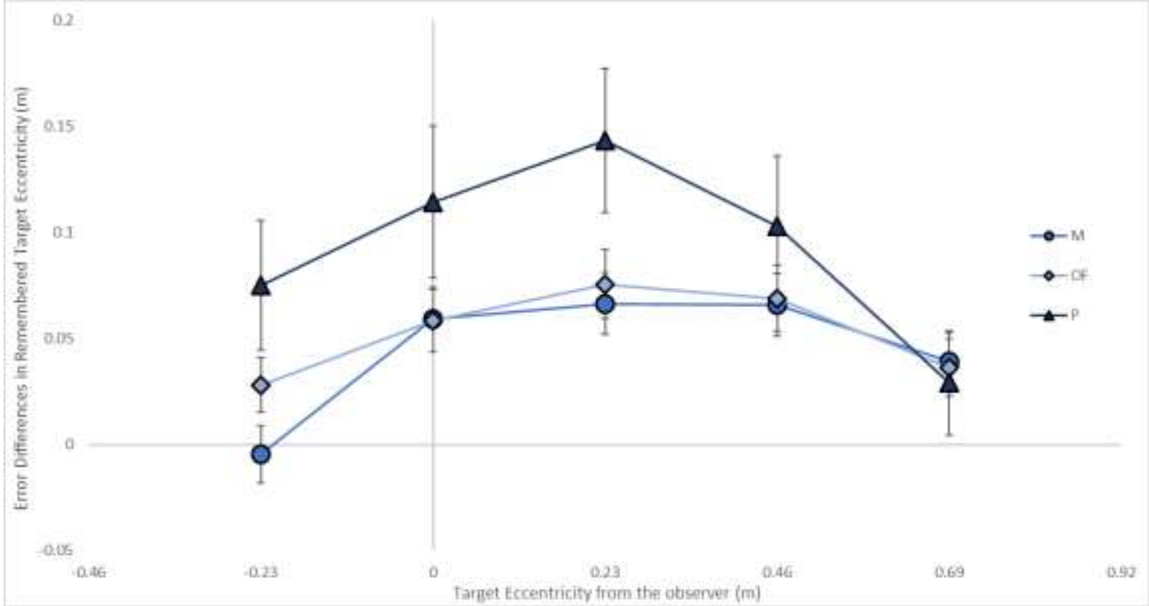


Figure 32: Exp 3 – Error differences between static and motion conditions. Error difference calculated by subtracting errors in remembered target location in static from the errors made after movement in each motion condition: M – full movement, OF – visually-induced moving, P – physical movement only. (+ values indicate greater errors after movement, - values indicate smaller errors after movement) The error bars indicate the standard errors.

Upon the analysis, a significant main effect of observer moving direction was found, *F* (1, 638) = 6.712, *p* = .010. The error differences were larger when moved to left (*M* = .075, *SD* = .133) compare to right (*M* = .053, *SD* = .134). A significant interaction between the movement conditions and movement directions was also found, *F* (2, 638) = 3.672, *p* < .026. Further evaluation revealed significant simple main effect of observer position, *p* < .001, where the error differences were significantly different between left and right movements for physical-only condition. When moved physically-only (P) the average error differences were .120m when moved to left, and .066m when moved to the right (*Figure 33*).

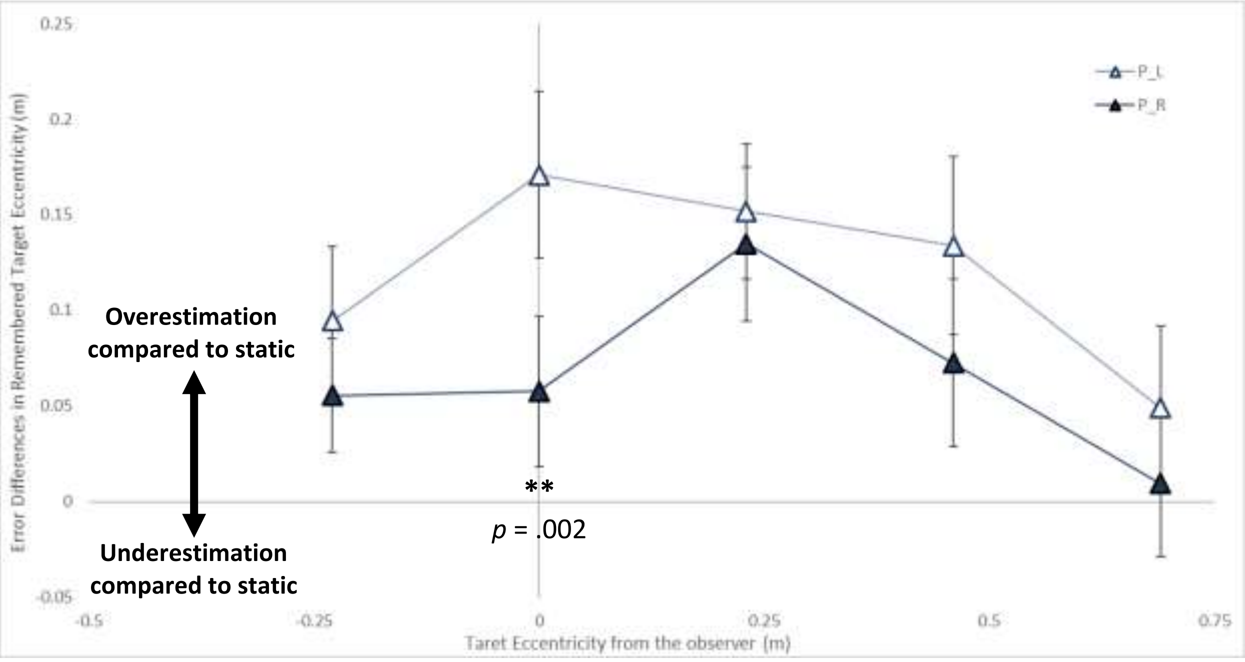


Figure 33: Comparisons of the error differences between left and right movement - Physical-only condition (P): L – moved to the left, R – moved to the right. The error bars indicate the standard errors.

5.8. Discussion of Experiment 3

5.8.1. Effect of perceived distance.

The significant positive correlation between the perceived screen distance and the remembered target eccentricity errors in static condition was not expected. When static, the observer can infer target location based on its direction. Because the target direction from the eyes is different from the direction from the right hand, the pointing direction depends on the distance of the target which may have influenced the errors made. If that were the case, however, the errors made from the left side (most targets on the right side) should differ from when they were on the right side (most targets on the left side) (see *Figure 26*). In experiment 1, this difference was already demonstrated when people showed bias towards right side when they had to rely on their right arm to point at targets without any visual feedback (see Section 3.6.3). Misperceived initial target distance may have influenced the pointing direction, rather than the remembered target location. Despite this possibility, in experiment 3, the errors did not differ between the two observer positions (see Section 5.7.3). Which makes sense, since the pointing bias toward the right side disappeared when a red-dot was displayed on a dark surface in their pointing direction in experiment 1 which was also shown in experiment 3 (see Section 3.7). Also, there was no effect of perceived distance found in the other experiments. It is probable that the correlation found was driven by only a few participants with extreme errors in either perceived distance or remembered target eccentricity errors (see *Figure 27A*) The correlation found here may be due to these possible outliers.

There was no correlation found between perceived distance and the remembered target eccentricity errors in any of the moving conditions which was consistent with experiment 2. The largest error in perceived distance was 126% for the experiment 3, but it was still not as large as some errors found in experiment 2. Also, I tested participants' stereopsis before they partook in the experiment. Therefore, it is unlikely the non-significant correlation found is due to participants' stereopsis as I suggested in section 4.7. Based on these results, the screen's perceived distance appears to have no consistent effect on updating after lateral movement.

5.8.2. Remembered target location shift after moving.

Consistent with the data from experiments 1 and 2, participants underestimated target eccentricity with the magnitude of the errors correlating with target eccentricity. Remembered target locations were shifted in the direction of movement after visually-induced lateral motion (approximately 3.70% of the visual movement on average) and when the visual motion was accompanied with physical motion (approximately 4.35% of the full movement on average). These shift values were much less compared to the experiments 1 and 2 where the average shifts after visually-induced lateral translation were approximately 20% of the movement distance. One possible reason for this difference in the shift magnitude may be the reduced travel distance. Updating errors people make are larger with longer displacement size (Gutteling & Medendorp, 2016). The mean error after visually-induced movement was 0.053m for the experiment 3 with movement distance of 0.46m, but the mean error for experiment 2 with movement distance of 1m was 0.081m which supports the previous finding. The reduced shift may be partially due to the reduction in the magnitude of errors with the shorter movement distance. The virtual screen in which the targets were presented was also closer in experiment 3 (1.75m) than experiment 1 and 2 (2m) which may also have contributed to the shift magnitude reduction.

Another possible explanation is the prior exposure to the real test room identical to the virtual test room. In this experiment, our participants had to spend approximately 15 minutes in the real test room to answer pre-test questions, listening to the instructions, and walking to the MMS platform to sit on the seat before to putting on the VR HMD for the test. In experiments 1 and 2, participants were sitting in a small office room which was very different from the virtual test room. Interrante, Anderson, and Ries (2006) found that misperception of distance in VR disappeared when participants were exposed to the real world environment, doing a walking task, prior to the identical virtual world environment. This prior exposure to the real test room may have resulted in the more accurate perception of the virtual environment, hence more accurate updating. Seeing the MMS, as well as experiencing real motion prior to visual-only condition, may have also primed the participants for physical motion and enhanced the effectiveness of visually simulated motion (Riecke, Västfjäll, Larsson, & Schulte-Pelkum, 2005), again possibly resulting in more accurate updating.

Curiously, the shift after physical-only movement was in the opposite direction of movement (approximately 6.30% of the physical movement on average) which means people overestimated target eccentricity after the physical-only movement. This overestimation represents overestimated movement distance with physical motion cues which is compatible with the past findings (Harris, Jenkin, & Zikovitz, 2000). Without vision, people need to rely on physical senses which are unreliable compared to vision in general. Relying on non-visual senses may make people uncertain of how much they moved, resulted in people overcompensating when pointing at the target location, hence overestimating the target eccentricity. This focus on the non-physical senses may also explain the asymmetricity in the error increase after moving to left compared to moving to right without vision (*Figure 33*). In experiment 1, people showed rightward bias for the targets on the right side, and after moving to left, most of the targets are located on the right side. After moving without vision, people may be more sensitive with their proprioception amplifying their arm-movement and overcompensate even more. Also, there was no parallax cues during the movement to infer distance without the vision.

5.8.3. Targets within the range of movement.

The remembered target eccentricity errors for the targets within the range of movement (this time including the targets at the initial and the final position of the observer) differed compared to static, not only after visually-induced motion as found in experiments 1 and 2 but also after physical motion. This result further confirms that lateral movement affects updating targets within the range of movement. Unlike in experiment 1 and 2, people did not become more accurate after moving but rather targets were remembered as more eccentric compared to static showing that moving does not enhance memory of the target location as I suggested in section 4.7. The same effect was found after physical-only movement for four out of the five targets (targets at -.23m, 0m, +.23m, and +.46m eccentricity after moving).

Based on these results, it appears that people remember the targets as more eccentric after lateral movement compared to when static. This overestimated eccentricity may be due to the initial error made before the movement (underestimation made at the observer's initial position), which then people make additional error after moving (underestimation made at the observer's final position) from that initially remembered target location (see *Figure 28* and *Figure 29*). The secondary errors after moving may be smaller for the targets within the range of movement, therefore the remembered target locations for these targets are closer to the initially remembered locations than the ones outside the range. To confirm this idea, more targets outside the range of movement will be needed in future experiments to compare errors made for targets within and outside the movement range.

5.8.4. Visual and physical cues on updating after lateral translation.

Some of the past studies suggested that people require both visual and physical cues for updating. My result show that the updating performance with visual cues only is as good as updating when both visual and physical cues are available, suggesting that people may not need (or at least not use) physical cues when visual cues available during lateral motion.

When only physical cues are available, people could still update to a degree. The errors made after physical-only movement were larger than errors made without movement (see section 5.7.3). The average updating errors made after physical-only movement was .061m (13.3% of the actual movement distance) which is larger than the errors made without movement (-.032m). If physical cues cannot be used for updating (gain of 0), the errors people make after physical-only movement would have to be similar to, or the same as, the errors made without movement which was not found in this experiment.

6.0. General Discussion

In this thesis I showed how spatial updating is affected by target eccentricity, passive lateral movement, and visual and physical motion cues during the movement. Throughout these three experiments, I demonstrated that perceived locations of the targets in front of the observer are dependent on target eccentricity. Updating after lateral translation depended on the range of the movement, i.e., initial and final target eccentricity. It was also found that people can use physical motion cues for updating after passive lateral movement, but these cues are not needed when visual cues are available.

When comparing the results to the hypotheses (see section 1.5): 1) the remembered target location errors were not smaller with both physical and visual motion cues compared to only visual cues, showing that people updating with visual cues alone are as accurate as they are with both visual and physical cues. 2) the errors were smaller with both motion cues compared to only physical cues, showing that physical cues alone may not enough for updating. 3) the errors after lateral movement when only physical cues are available were smaller than the distance participants traveled, which shows physical cues can be used for updating to some degree (see section 5.8.4). 4) remembered target locations were not more eccentric for people that perceived the virtual scene as further away, suggesting that perceived distance may not affect updating at least for the screen distance tested here.

6.1 The Effect of Eccentricity

The perceived target eccentricity of targets projected on a wall around 2m in front of an observer are underestimated (perceived as closer to the observer than they are). Not only that, the amount of underestimation depends on the eccentricity of the target (the more eccentric the target is, the larger the underestimation). When static, the average gain, the remembered target eccentricity compared to the actual target eccentricity, was .83. This is compatible with the study by Prablanc and colleagues (1979) where people undershot when they reached for a target location (a red LED) with their right hand that turned off turned off at the onset of the observer saccade. In this study, the gain was approximately .84 (derived from the graph from *Fig. 2* in their paper). Unlike Prablanc and colleagues' study, however, the targets for the present study were out of the observers' arm's reach (the distance between the eyes of the observers and the screen, where the targets were presented, were: 2m for experiments 1 and 2, and 1.75m for experiment 3). This trend of underestimating target eccentricity as eccentricity increases shown in my experiments (see *Figure 17*, *Figure 23*, *Figure 28*, *Figure 29* and *Figure 30*) demonstrates that this effect may extend to the targets that are not reachable.

Another study, Vercher, Magenes, Prablanc and Gauthier (1994) had participants point at targets at different eccentricities (10°, 20°, 30° and 40°) but at a constant distance (along a circular radius of 60cm from the participants' head center). People generally undershot target eccentricity (target direction in degree) as well as distance, but there was no significant increase in errors for more eccentric targets (average gain of .99; derived from the graph from *Fig. 4A* in their paper). I presented targets on a wall at a fixed distance away from the observer, hence both eccentricity and distance varied for each target. The underestimated target eccentricity found in the present study may be due to underestimated target distance, which increase as the target gets further away (Allison et al., 2009; Palmisano, Gillam, Govan, Allison, & Harris, 2010), rather than from underestimated target's angular eccentricity.

6.2. Switching Hemispheres

The visual field of each eye is divided into left and right hemifields, the image projected on retina cut down in the middle with fovea in the center. Because of the optic chiasm, the visual signals from left hemifields are sent to the right hemisphere, and the signals from the right hemifields to the left hemisphere of the brain. The targets that were most affected by lateral self-motion were the ones within the range of movement. These targets changed side relative to the observer after the movement, either start on the left hemifield before moving on the right after moving or vice versa, hence changing hemifield (see *Figure 34*). When a remembered visual target location reverses sides during motion, relative to the observer's gaze direction, the internal representation of the target is remapped onto the opposite cortical hemisphere (refer to the *Fig. 4* in the paper Gutteling et al., 2015). This switch in hemisphere is observed in human parietal area after eye movement (Bellebaum & Daum, 2006; Merriam, Genovese, & Colby, 2003), as well as after full body movement (Gutteling & Medendorp, 2016; Gutteling et al., 2015). For this cross-hemispheric switch to happen, the information of the target from one hemisphere must be sent to the other hemisphere. Berman and colleagues (Berman et al., 2019) surgically removed the corpus callosum of rhesus macaques that were trained to do double-step tasks, making visually guided saccade to target 1 then a memory-guided saccade to target 2, splitting their brains to left and right hemisphere that could no longer communicate. They found that split-brain monkeys were impaired on the double-step sequences that required updating across hemifields, indicating that the information does need to cross hemisphere. Such a crossing process may take more time, as the updating process after saccade was shown at about 50ms after saccade offset (on the hemisphere contralateral to the target hemifield) while the shift of the target stimulus to the opposite hemisphere was shown at about 400ms after saccade offset (Bellebaum & Daum, 2006). However, I used full body movement (5 and 7 seconds) which took much longer than a typical saccade (less than 100ms) which may have less impact from this delay.

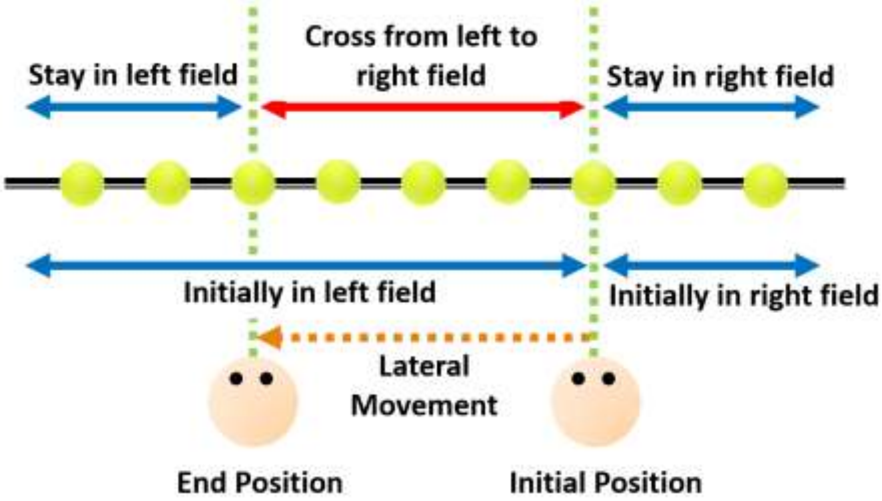


Figure 34: Change of the target visual field after observer lateral movement based on the target eccentricity. Targets within the range of motion (indicated by the red arrow) are initially in the observer's left field but switch to the observer's right field as a result of the movement. Targets outside this range merely move within their original fields.

Although the present study does not include many targets in the “not crossed” category, the results from all three experiments suggest people remember the “crossed” target location after lateral movement closer to the location remembered before moving compared to the “not crossed” targets (except for physical motion only condition). Ecologically, people try to keep an important target in the center of their visual field (e.g., when a person is chasing a football). However, if the person, the target, or both move, the target will keep shifting between the hemifields. It is possible that people are more accurate at keeping track of objects that cross hemifields for this reason. Despite the findings from the present thesis, further study (such as using up-down self-motion to prevent hemifield crossing while keeping the target eccentricities) is required to determine whether the effect is indeed from the target crossing hemifields.

6.3. Updating during Lateral Linear Vection

People can keep track of object locations during passive rotation using visual cues only when the scene used is a naturalistic virtual environment they are familiar with (Riecke, Heyde, et al., 2005). In fact, just presenting them with a static image of new orientation in the virtual environment, without providing continuous-motion information, can be enough (Riecke, Heyde, et al., 2005). To do this, participants would need to use landmark cues. Pure optic flow patterns, such as from a grayscale texture (Riecke et al., 2007), or an unfamiliar virtual scene (Riecke et al., 2012) have been reported as being insufficient to be used for updating the target location after rotation.

Updating is directly related to perceived self-motion. Studies looking at updating found that people overestimate self-motion with linear forward vection with constant velocity (Harris, Jenkin, Allison, Jenkin, & Felsner, 2012; Redlick, Jenkin, & Harris, 2001). However, these studies used forward motion when laminar (lateral or vertical motion) and radian (fore/aft motion) flow requires different computational mechanisms (Harris, Jenkin, Allison, Jenkin, & Felsner, 2012). The vection-onset latency, time it takes for people to feel vection, differs between upward-downward (laminar; median latency at 3.52s) and forward-backward (radian; median latency at 4.67s) flows (Giannopulu & Lepecq, 1998). Perceived self-motion from lateral vection may also differ from the forward vection. In horizontal direction (left-right), in large field of view, the average onset time for vection was found to be ~7s (Keshavarz et al., 2017) which suggest most participants in my study would not have felt vection. Despite this fact, the performance with visual-only motion was at par with the full motion in experiment 3. It may be the result of motion priming suggested in section 5.8.2, reducing the vection onset time, or they may be using information other than self-motion for updating.

Unlike rotation, a naturalistic visual scene without familiar landmarks was sufficient for updating during forward motion (Riecke et al., 2012) and possibly for other linear translations. I removed landmarks by having our participants perform in the dark – I was interested only in how lateral vection could be used for updating. It is unclear whether the virtual scene used was familiar enough for the participants after the exposure to the real test room, as explained in section 5.8.1. However, the results here show that visual cues are enough for updating after passive lateral translation, at least as much as when compared to both visual and physical cues are available.

6.4. Updating with Vestibular Cues

Participants' updating performance when their motion was simulated with visual cues alone (vection) was not significantly altered when they had both visual and physical cues to motion available. Although we used a constant velocity for our lateral translation, of course this requires an acceleration at the beginning and end of the motion (see *Figure 9*) and participants were very aware that they were moving in both the light and dark conditions. When a person was moved during the test, the motion platform accelerated rapidly at its maximum capacity at the initial position and decelerated rapidly until stop at the final position. Because the vestibular system can only detect accelerations, the vestibular cues were only available at the start and the end of the movement making vestibular cues unavailable during the translation period. To produce more reliable vestibular cues and evaluate their roles, future study should implement constant acceleration motion profiles rather than constant velocity.

6.5. Effect of Perceived Distance to Updating

There was no solid evidence found that people's perceived distance has any effect on their updating after lateral movement. Although significant correlations were found in some experiments (after visual motion in experiment 1, and static condition for experiment 3), the effect was not consistently evident throughout the study. The experiments, however, shows very large individual differences between the participants where perceived distance of the participants ranging between 79% underestimation to 305% overestimation of the distance to the screen. I also only used one fixed screen distance for each experiment which may not be enough to reveal the influence of people's distance perception to updating. To look at the effect of people's perceived distance, or their scaling of the environment, on updating, future studies should incorporate multiple target distanced into the experiment.

6.6. Limitations

6.6.1. Restricted range of target eccentricities.

Although I found some interesting effect of lateral movement for the targets within the range of movement, that had to be remapped across hemisphere, I did not have many targets outside the range. To evaluate whether this effect was truly resulted from the targets processed trans-hemispherical, compare between the "crossed" and "not crossed" targets, future study should add more targets outside of the movement range.

6.6.2. Restricted range of target distances.

As stated in the section 5.0, introduction of experiment 3, the originally plan to conduct the experiment in both the real and the virtual test room to evaluate the effect of perceived distance in spatial updating was not done due to the technical difficulty. Instead, I measured participants' perceived distance and correlated them to the errors they made. However, I only used one screen distance and could not come to a firm conclusion on how the spatial size affect our updating (see section 6.5). Multiple target distances should be used in future studies to look at whether misperceived distance affect updating after moving.

6.6.3. Vestibular stimulus.

As explained in section 6.4, we used a constant velocity for our lateral translation which may lack the vestibular cues at some portion of the movement. To produce more reliable vestibular cues and evaluate their roles, future study should implement profiles with varying acceleration motion profiles rather than constant velocity.

7.0. Conclusions

When updating an object location after lateral movement, people need to know the initial distance and eccentricity of the object then compute the final distance and eccentricity based on their self-motion. In my experiments, people also had to point at the updated location with their right hand which requires knowing the pointing angle. When doing so, people make systematic errors pointing at the remembered location of a target in front of them, underestimating its eccentricity. Then also make additional underestimation pointing at the new location following a passive lateral movement. These errors depend on the initial and final eccentricity of the object, the ones within the range of movement being remembered as truer to the initially remembered object location before moving. However, updating does not seem to be influenced by people's individual perceived distance of the target. Such moving-range-dependent updating can be beneficial for interacting/avoiding objects within the path or remembering the location of an important landmark after passing it when walking around (active movement) as well as when on a wheelchair or driving around (passive movement). However, correctly perceived initial location of the object, and self-motion are still needed to update their location accurately.

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