INFLUENCE OF ACTIVE CONTROL ON MOTION-INDUCED POSITION SHIFT IN A 3-DIMENSIONAL SETTING

by

Joseph Muscat

A dissertation submitted in partial fulfilment of the requirements for the

Master of Science in Cognitive Science

Department of Cognitive Science

Faculty of Media and Knowledge Sciences

University of Malta

2019

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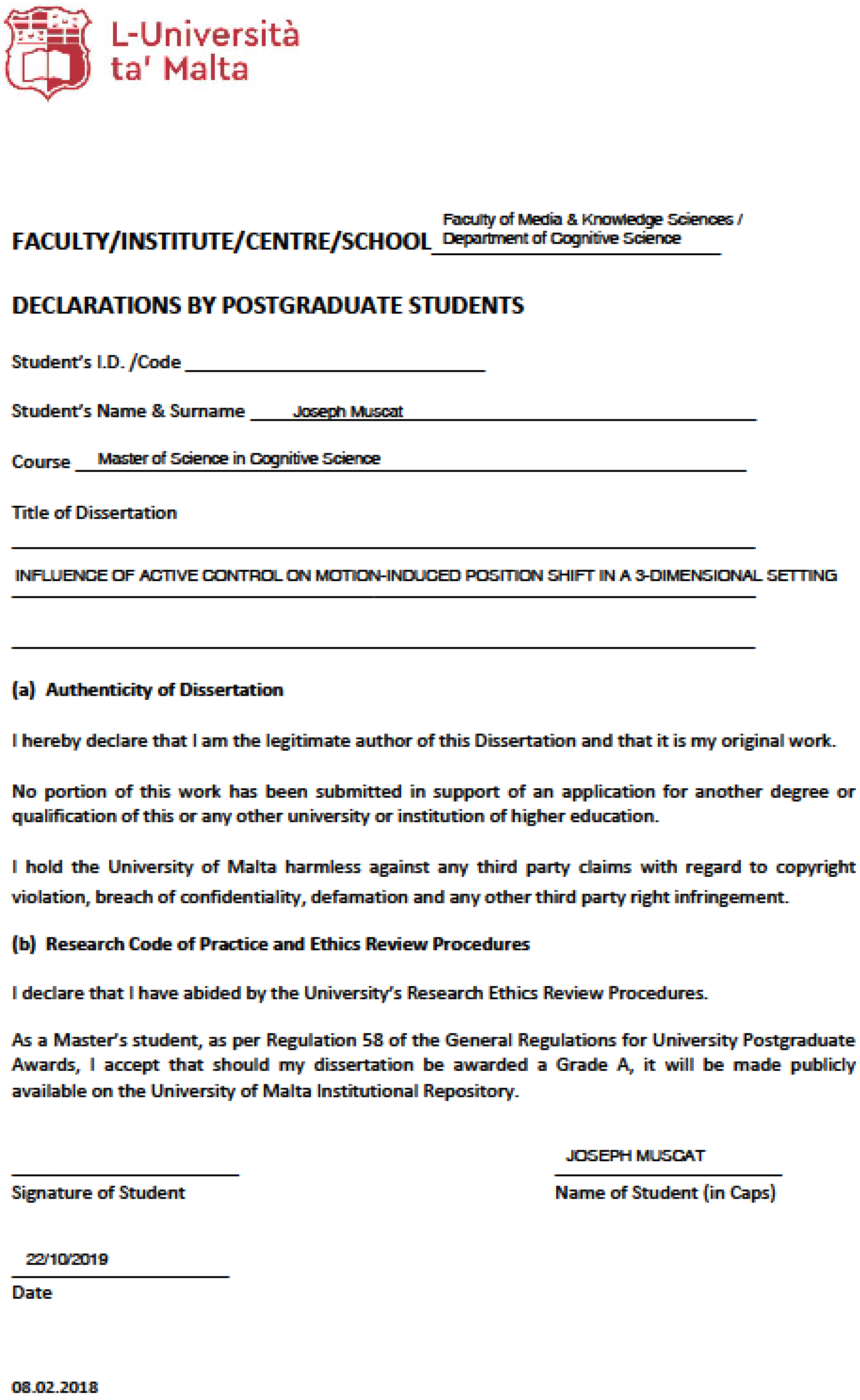

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Student's Name & Surname Joseph Muscat

Course Master of Science in Cognitive Science

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Abstract

It is well known that the perceived location of an object can be considerably influenced by motion signals. The position of a stationary Gaussian window with a locally drifting sinusoidal grating - a Gabor patch, appears to shift in the direction of motion of the carrier stimulus. This robust, illusory phenomenon is referred to as motion-induced position shift (MIPS). It has also been theorized that actions are less prone to visual illusions than are perceptions because the same visual information is coded through anatomically distinct pathways and in a different way for perception as for action. Recent studies have used the motion-induced position shift illusion to explore the effect of active control on the perceived physical position of a target. The results indicated that action systems not only are unable to counteract this form of visual illusion but indeed that the illusionary effect was consistently larger under active conditions. These studies, like much research to date has typically presented the stimuli in a frontoparallel, 2-dimensional plane. To pursue the possibility of creating a more ecologically valid stimulus presentation, this study had the goal to explore the influence of motion-induced position shift during active perceptual tasks in a 3-dimensional setting. For this purpose, a novel game experiment was created using Unity3D to measure and analyse the effect of action under globally moving but locally static or drifting visual stimuli. In one task, participants were required to follow with a drifting Gabor patch a curving line along the floor of a virtual tunnel. The other task entailed participants steering the Gabor to collide with block objects lying along the floor of the tunnel. Clear evidence suggesting an effect of embedded motion on global positional error was recorded in both tasks. The current study suggests that the influence of the illusory position shift due to motion extends to action performed in a 3D setting.

Mislocalization of position due to motion is not merely an academic oddity, but can also have real life consequences. Every day, people are required to make judgements about what actions to execute based on what they see and safety research recognizes the import of the influence perceptual visual biases can have on this choice of action in human-machine interactions. This research also adds to the understanding on how these interactions can be designed such that unsafe outcomes can be predicted, avoided or eliminated.

Dedication

As always, dedicated to the two M’s in my life.

Acknowledgements

A special word of thanks to my supervisor, Prof. Ian M Thornton for his guidance and inspiration.

Also, a word of gratitude to all the faculty of the Department of Cognitive Science who opened up new vistas of knowledge for me hitherto unexplored.

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1 Introduction

Movement is ubiquitously evident in our ecology and surroundings - we experience a world full of motion. Almost all living organisms having the capacity to move, use movement as a crucial source of information about the environment and consequently as an essential faculty to live and survive (Park & Tadin, 2018). Our biology and perceptual capabilities are the result of evolutionary processes that have adapted cognitive systems to serve these demands (Hoffman, 2018). Indeed, this ubiquity and essential significance of movement in our world is reflected in how our visual system has evolved as exceptionally good at perceiving and processing motion (Park & Tadin, 2018). Likewise, determining the position of objects in visual space is one of the principal functions of vision (Whitney, 2002). This process of localization is not only contingent on position in retinotopic maps but also on other influences like the motion signal (Linares, López-Moliner, & Johnston, 2007). However, although in Newtonian physics, motion is determined from position changes over time, this is neither a sufficient nor necessary condition for motion perception. On the one hand, the phenomenon of “apparent motion” (Ramachandran & Anstis, 1986; Pizlo, 2001; Freyd & Finke, 1984) – the percept of flowing movement from stationary stimuli - shows that subjectively our sense of movement can be formed from discrete alterations of location in time. Though, variations in retinal image locus during saccadic eye movements are not detected as movement of the visual world (Bridgeman, Hendry, & Stark, 1975). On the other hand the sensation of motion can be induced by static stimuli. The illusion known as motion after effect (MAE), where a stationary test pattern appears to move in the opposite direction after adaptation of the visual system to motion of a pattern in a particular direction, is one such example (Whitney, 2002). Another example where motion is perceived from a completely static image is the well-known “rotating snake illusion” (Kitaoka & Ashida, 2003).

From the above it is seen that while human visual perception is mostly very accurate, motion signals can also be uncertain and occasionally differ from our perception such as in the case of visual illusions (E. Watanabe, Kitaoka, Sakamoto, Yasugi, & Tanaka, 2018). Nonetheless, we seem to have the ability to sense motion fluently and veridically over an extensive variety of motion inputs (Park & Tadin, 2018) and for most people, vision is an essential guide for implementing successful actions (Marinovic, Plooy, & Arnold, 2012). Studies have investigated how given these illusive perceptions, humans still functionally interact successfully in real-life contexts with the numerous static and moving objects in their surroundings or more specifically the cognitive system links between perception and action (Caniard, Bülthoff, Mamassian, Lee, & Thornton, 2011). This current study aims to extend this research by further exploring the influence of perceptual illusions during active vision. Specifically it is intended to study the effect of active control in a simulated 3-dimensional environment thereby reflecting a more ecological setting. In the following section a brief review of the underlying knowledge and relevant research that has been done in this area will be presented.

2 Literature Review

2.1 Motion Analysis

Visual animals process the optic input to their eyes into visual information that steers their actions many of which are contingent on estimating movement. Specifically, sensory systems use receptors to abstract data from their surroundings and extract motion velocity vector information of direction and speed by combining light intensity signals over space and time. Subsequent neural circuits execute ensuing computations to estimate motion. In visual motion psychophysics and neuroscience, how evolution has resolved this problem is approached independently in two conceptual ways – the mathematical modelling of the transformation process algorithm from input to output signals and by how neural processes implement these models biochemically (Clark & Demb, 2016). Beyond describing the local, isolated motion-vector signals there is also the general question of how these local motion signals are integrated into a global percept (Cropper, 2001). These topics of visual motion research will be discussed in the following sections.

2.1.1 Local motion

In biological vision systems, analysis of motion begins with local signals such as for example, the extent of output from directionally selective cells in the primary visual cortex (V1) (Nakayama, 1985). These neurons maximally respond to orientations aligned with their preferred directions, while presenting minimal reaction to opposed, counter-preferred, oriented bars moving across their small receptive fields (Park & Tadin, 2018). The first cortical visual area with direction-sensitive neurons is V1 and it is therefore deemed to be the site of early local motion detection.

The essential elements of motion are direction and speed and to perceive motion, the visual system should have the ability to dependably recognise spatial and temporal changes. One model developed by Adelson & Bergen (1985) applied Fourier analysis to visual perception. It conceptualized that at a local level, any motion sequence may be represented as an orientation in space-time (an x-y-t plane). At a minimum, a retinal image is a function of the two spatial dimensions x and y and to have temporal sensitivity as well, a signal that is a function of three variables: x, y, and time (t) is necessary. In this model, the basic stimulus assumed for vision is the sine wave grating having two frequencies - the spatial frequency and temporal frequency of the wave. For any constant point in time, the visual signal will be a sin wave which is periodic in space having a spatial frequency, while for any fixed point in space, the signal will oscillate over a regular period in time which is the temporal frequency component. Adelson & Bergen (1985) showed that motion information can be obtained by a system that reacts to this oriented spatial-temporal energy and human motion perception can be well modelled by appropriately tuned spatial-temporal filters (Burr & Thompson, 2011). It has been shown that such orientation selectivity occurs in neurons of the primary visual cortex (V1) area of primates (Hubel & Wiesel, 1968; Movshon, Adelson, Gizzi, & Newsome, 1985). Additionally, functional grouping for this selectivity is also seen: “neurons are organized in a columnar fashion with shared orientation preference across cortical layers and smooth changes in selectivity along the V1 surface.” (Pattadkal, Mato, van Vreeswijk, Priebe, & Hansel, 2018).

From the above, motion of objects in our visual landscape leads to complex patterns of spatial-temporal luminance fluctuations on the retina which the visual system senses and deconstructs to their spatial and temporal components in V1. To form motion perception, these components are then suitably integrated along a cascade of extrastriate areas to more complex representations (Jogan & Stocker, 2015). This integration is considered to take place in the medial temporal (MT) area, which is the first extrastriate area that receives direct input from V1 (Zeki, 1974).

2.1.2 Perceiving speed

This spatial-temporal energy model and other similar ones were demonstrated to be quite effective in perceiving motion direction, however less so in determining speed. There is more doubt about the processes behind speed encoding in perception (Burr & Thompson, 2011). A number of factors have been found to influence speed perception which indicates that it is more complex than simple detection of local speed signals. Of these factors, the most extensively researched has been the control of contrast on perceived speed (Park & Tadin, 2018). Studies indicate that a high-contrast stimulus will be seen as apparently moving quicker than a lower-contrast stimulus that is similar in other respects – a phenomenon known as the Thompson effect (Stone & Thompson, 1992; Stocker & Simoncelli, 2006).

The current foremost models that explain such effects or ‘biases’ in speed perception invoke a Bayesian framework which hypothesizes that probabilistic inferences about external reality can be made based on sensory inputs. The Bayesian approach is founded on Bayes’ theorem for making estimations and choices under conditions of uncertainty (Soon, Dubey, Ananyev, & Hsieh, 2017). This optimal ‘ideal-observer’ model – an ideal-observer is a notional mechanism that conducts allocated tasks with optimal efficiency - is based on a statistical manifestation of von Helmholtz’s (1924) view of perception as a ‘best-guess’ of what is in the environment, given both the sensory input and prior experience (Stocker & Simoncelli, 2006). On this view the principal aim of an ideal observer given the stimulus on the retina is to calculate the probability of each possible valid state of the world (Geisler & Kersten, 2002). This requires to be quantified in applications of Bayes’ rule by specifying what makes a best-guess best and how that guess should be influenced by prior experience (Weiss, Simoncelli, & Adelson, 2002). A critical prior belief assumed by these models is that in our experience objects in nature tend to be stationary or move slowly. The Bayesian combining of this prior belief with high sensory stimulus uncertainty would produce an optimal perceptual inference by the visual system. Simplifying, when stimulus contrast is low, uncertainty is high and motion perception is more reliant on prior bias leading to an inferred perception of slower speeds.

Applying this model Stocker & Simoncelli (2006) showed that a Bayesian estimator can deliver a precise prediction of human visual speed perception across a wide range of stimuli including contrast-dependent percepts like the Thompson effect. More recently a model that combines biological constraints with a prior belief that low speed objects have higher probability, the so called ‘Bayesian slow speed prior’, was shown to describe a wide variety of speed percepts (Sotiropoulos, Seitz, & Seriès, 2014). Further model development by Jogan & Stocker (2015) established that a Bayesian framework that optimally integrates visual speed data across different spatial-temporal frequency channels can accurately predict visual speed perception and provides a unifying explanation for the reported influence of stimulus contrast and spatial frequency on perceived speed.

2.1.3 Global Motion

Sensing local motion stimuli is a crucial stage in processing visual motion but is insufficient in explaining motion perception. Since local motion signals can be ambiguous, reliable motion perception requires integration of signals over larger regions (Park & Tadin, 2018). Various studies in both humans and non-human primates indicate that this spatial integration of motion signals begins in the middle temporal (MT) area, which takes direct input from V1 (Furlan & Smith, 2016).

To determine the true global motion of the object, local motions must be combined in some way and how our perceptual experience is portrayed by integrating local motion signals into more global motion representations, has been an important question for motion research (Burr & Thompson, 2011). As mentioned above, the integration process is necessary because initial local motion signals are ambiguous. The phenomenon referred to as the ‘aperture problem’ is such an example equivocal about the direction of motion and speed. It results from V1 neurons responding to motion contours viewed through an aperture, their small receptive field, which is smaller than the moving stimulus. Only the motion component normal to the contour can be ascertained which results in ambiguous local motion detection that would restrict the capability of the visual system to correctly perceive the velocity of the larger global objects (Bradley & Goyal, 2008). Perception of global motion entails the ability to attain some measure of a central tendency direction over a broad section of visual space comprising a diversity of local directions by integrating these signals over space and time (Furlan & Smith, 2016). Although substantial research has been carried out to-date, the characteristics of the underlying integration scheme remain unclear. Recently, parsimonious models explaining the aperture problem have however been suggested (Weiss et al., 2002) although this continues to be an active study topic.

Typical stimuli used in such studies are plaids and random dot stimuli. Plaids are generated when two drifting sinusoidal gratings of different orientations are superimposed.

The resulting global motion often experienced by an observer is a single ‘plaid’ pattern moving in a resultant direction arising from but different to the individual grating directions which are normal to their contours (Burr & Thompson, 2011). Most models account for this effect by one or a combination of three main rules - intersection of constraints (IOC), vector average (VA), or feature tracking (FT). In vector space all possible velocity vectors that are allowed and match with the motion of each grating form a notional constraint line. The (IOC) hypothesis argues that the perceived velocity of the moving plaid is determined by a vector formed at the intersection of the constraint lines of the two gratings. The VA explanation on the other hand, determines the plaid velocity as a resultant vector lying between the two gratings’ normal velocities obtained by averaging these vectors’ *x*- and *y*-components. In the FT solution the plaid velocity relates to the velocity of some feature of the plaid luminance intensity pattern (Weiss et al., 2002).

Application of these models has had limited success and often there are conditions where to predict a veridical motion percept an ad-hoc combination of rules is required. This suggests that these approaches are not be the only processes by which local motion signals are integrate in the visual system (Park & Tadin, 2018). Indeed a more unifying and alternative approach has been proposed by Weiss and colleagues (2002) who proposed a model based on a Bayesian framework that can predict the perceived velocity of any moving spatial-temporal stimulus including motion perception in plaids. The model makes the assumption that any temporal fluctuations in image intensity are wholly resulting from the translational motion of the intensity pattern. Additionally it makes two fundamental assumptions namely that perceptual data is noisy and that the experience of slower velocities is more likely in the environment. The Bayesian model that results predicts well how motion is perceived under a variety of conditions of uncertainty and provides explanations for apparent biases and illusions. While the model does not provide a complete quantitatively explanation for all conditions, it accurately predicts a wide range of effects (Weiss et al., 2002).

2.1.4 Motion segregation and transparency

As mentioned above, motion integration is crucial in removing ambiguity in local motion signals such as in the ‘aperture problem’. This mechanism is however only beneficial if it is limited to those local signals that pertain to a single surface. Motion perception would be vitiated if motion signals from different objects or from an object and its background are averaged (Park & Tadin, 2018). It is widely held that to solve this problem the visual system finds a balance between motion integration over space and time and motion segregation that by parsing the view into diverse areas enables concurrent perception of multiple objects (Braddick & Curran, 2002). A practical case of motion segregation which is of relevance to the current study is motion transparency. This is the ability to perceive superimposed surfaces sliding smoothly in different directions across the same part of the visual field (Burr & Thompson, 2011). These circumstances imply that the observer may simultaneously perceive the incidence of more than one velocity at a single location. The representation of these multiple velocity vectors in the same spatial area is a demanding task for the visual system and a challenge for conventional motion perception theories (Rocchi, Ledgeway, & Webb, 2018). Understanding the phenomenon of transparent motion has been shaped by some key findings. Under conditions of motion transparency V1 neurons respond with direction preference while MT neurons demonstrate an inhibited response. Other studies found that to sense transparency it was necessary for local motion signals to be unbalanced otherwise the percept of transparency breakdowns and the moving fields are seen as a single pattern. These led to the suggestion the initial processing of local motions at the scale of V1 receptive fields which would only recognise transparency if these motions are not balanced. Feeding these signals forward to MT’s larger receptive fields allows for multiple motion directions to be represented (Maloney, Clifford, & Mareschal, 2018). This model indicates that the visual system first segregates stimuli based on their direction of motion and then integrates them into the different surfaces which suggests that an intermediate non-linear process such a feature extraction is involved (Burr & Thompson, 2011). In fact studies have shown that characteristics related to target surfaces like depth, speed, spatial frequency and colour improve segregation and ensuing motion transparency perception (Maloney et al., 2018).

2.1.5 Motion and Position

Object movement generally happens together with changes in object displacement, however historically the motion and the position of an object were thought to be independent visual processes. Nonetheless, there are frequent occasions where motion and position interact and recent research has shown that there is a complex association between an entity’s motion and its position percept and their encoding in the brain is thought to be intricately interlinked (Whitney, 2002). Many studies have reported phenomena that show that the apparent position of an object in the environment is not only determined by the motion of the object but can also be strongly modulated by the presence of other motion signals in the visual field (Ye et al., 2018). This is indicative that visual motion processing is an integral component of visual positioning which takes into account an object’s motion when ascribing its location (Whitney, 2002). Further evidence of the implicit co-occurrence of motion and position is their bi-directional relationship (Park & Tadin, 2018); the perception of motion has been demonstrated even when there is no net first order local motion in the stimulus as in so-called attention-driven motion caused by creating attentional-tasks requiring participants to track cued features (Verstraten, Cavanagh, & Labianca, 2000).

2.2 Motion-Induced Position Shift

One phenomenon that suggests motion processing strongly affects estimates of position and which has been extensively studied is called “motion-induced position shift” (MIPS). Ramachandran & Anstis (1990) found that position shift illusions occurred in objects demarcated by kinetic edges. A kinetic edge is a border such as between two otherwise identical random-dot patterns except one is stationary and the other is moving. In this study, the window defined by the kinetic edge containing the moving dot pattern appeared to be displaced in the direction of the motion especially when the moving and static regions were at equiluminance. Subsequently, De Valois & De Valois (1991) showed that a moving sinusoidal grating (a drifting Gabor patch) within a statically positioned Gaussian window results in a shift in the perceived position of the Gabor in the direction of the grating's motion, even though the window's location does not change. It has also been observed that if viewed peripherally, a stimulus (e.g., Gaussian window) having both local motion (e.g., a drifting Gabor patch) in a particular direction and is itself moving with a global motion component in another direction, its apparent path will greatly differ from the actual trajectory. In fact the stimulus can seem to move obliquely from the point of fixation when it actually only follows the global motion path. This illusion is called 'infinite regresses illusion' or curveball effect (Tse & Hsieh, 2006; Shapiro, Lu, Huang, Knight, & Ennis, 2010).

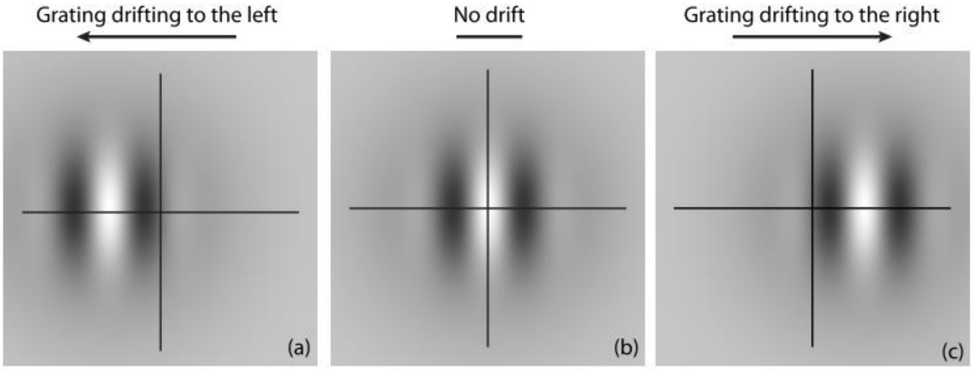


*Figure 1.*The effect of motion-induced illusory displacement on perceived global position.
In all panels, the crosshair indicates the true global position of the Gabor patch. When the grating within the patch drifts to the left (panel a) or right (panel c), perceived global position is also shifted in that direction. In the absence of local motion (panel b), perceived and physical position align.

MIPS ensues for many types of motion stimuli. One other version arises when a static objective is flashed near a stimulus in motion. Whitney & Cavanagh, 2000 recorded that an illusory displacement of two physically aligned flashes in the direction of the motion of a rotating radial grating. This effect is called the ‘flash drag effect’. Another closely related illusion that has been recently described (Cavanagh & Anstis, 2013). Called the ‘flash grab effect’, it arises when a moving stimulus undergoes a reversal of direction and a flash is momentarily displayed simultaneously and at the same position as the reversal. The flash is perceived to be robustly shifted in the reversed motion direction. Yet another demonstration of MIPS is called ‘positional motion aftereffect’ (MAE) which ensues when a fixed target is shown after motion adaptation (Park & Tadin, 2018). Nishida & Johnston, 1999 showed that after adaptation of the visual system to a rotating windmill, a static test windmill displayed in the adapted region seems to be displaced in the direction of the motion aftereffect. The original motion causing the MAE seems be distorting position indirectly with the MAE motion playing a part in the coding of the location of the test object (Whitney, 2002). These manifestations of MIPS and variations thereof have been used by researchers to investigate the physical and perceptual factors that influence the illusion and thereby underlying mechanisms.

Although De Valois & De Valois (1991) originally stated that the extent of apparent displacement of MIPS is influenced by the spatial frequency of the stimulus, McGraw et al. (2002) disagreed and reported that illusory positional shift was found to be unaffected by changes in spatial frequency. Indeed, the maximal shift percept appears at a relatively fixed temporal frequency range (4 – 8 Hz) for both low spatial frequency gratings (0.18 – 0.71 cycle/degree) (Bressler & Whitney, 2006) and middle spatial frequency (2 cycle/degree) stimuli (De Valois & De Valois, 1991). The extent of the illusory MIPS for drifting first-order Gabor stimuli was shown by Bressler & Whitney (2006) to increase with temporal frequency then flattens off at a point dependent on the carrier spatial frequency. This is in line with findings from other experiments (De Valois & De Valois, 1991; McGraw et al., 2002). Contrast of the grating does not seem to influence the MIPS illusion (McGraw et al., 2002) for a drifting first-order Gabor stimulus, however changing its Gaussian luminance window to a hard aperture drastically reduces the effect (Whitney et al., 2003). As the stimulus' retinal eccentricity is increased there is also an increasing apparent positon bias in the direction of grating motion with the magnitude increasing with eccentricity at a rate of around 1–2 minutes-of-arc per degree of eccentricity (De Valois & De Valois, 1991; Fu, 2004). A study by Arnold, Thompson, & Johnston, (2007) found that the MIPS effect can increase linearly with increasing stimulus exposure duration and then plateau. This steady-state was observed after exposure durations of 180 ms at a stimulus drift speed of 7.5 degree/s and at 100 ms for a drift velocity of 16 degree/s (Chung, Patel, Bedell, & Yilmaz, 2007).

In positional MEA conditions, position spatial shifts can be perceived even when observers are not aware of the inducing motion direction (Whitney, 2005). However, a study by K. Watanabe, (2005) showed that the motion-induced position shift disappeared when stimulus motion is removed from visual awareness by binocular rivalry suppression.

Most of the above findings about factors effecting MIPS were observed in the context of luminance-defined motion, also known as first-order motion. However Bressler & Whitney (2006) found that drifting second-order Gabor stimuli also exhibit an illusory position shifts. **S**econd-order motion is carried by the modulation of features other than luminance properties such as texture or contrast which does not result in an increase in luminance or motion energy in the Fourier spectrum of the stimulus (Park & Tadin, 2018). It was observed that dependence of the second-order MIPS on temporal-frequency is band-pass over a relatively restricted range centred at approximately 4 Hz, and is more or less unaffected by spatial frequency. On the other hand, further later research obtained only a relatively small second-order position-shift (Pavan & Mather, 2008). Various other reports have shown that illusionary position shifts are not induced exclusively by local motion signals. Rumi Hisakata & Murakami (2009) found that plaid motion also produced a shift percept in the direction of global motion could not be predicted by the averaging MIPSs ascribed to local component motions. Other results showed that MIPS from plaids' drift is greater than the shifts obtained from local component motions (Mather & Pavan, 2009). However, although the perceived motion is the global motion and is influential on the size and direction of the MIPS, Kohler, Cavanagh, & Tse (2015) found the apparent position direction was closer to that of the component motion. This showed that despite global motion having an evident influence on position shifts, it is the component motion that is the primary factor in its setting.

Since objects in natural scenes are usually three-dimensional and are perceived to move in three-dimensional space, it is pertinent to study if MIPS is evident in such a scenario. Tsui et al. (2007) investigated if this effect exists in stereo depth defined using binocular disparity and found that motion signals can indeed elicit an illusionary shift in depth which is analogous to that perceived by motion within an object in a two-dimensional plane.

Novel research by R. Hisakata, Terao, & Murakami (2013) went beyond studying MIPS in static situations having fixated eye gaze and a stationary envelope with only the carrier drifting (fixation). They considered that at least three factors could otherwise influence MIPS namely envelope-relative velocity, retina-relative motion, or display-relative motion to the grating's temporal drift and wanted to determine if the illusion would be induced when eyes or envelope were moving and if so which carrier relative motion induced the effect. In a series of experiments the researchers independently controlled the motions of the envelope, the carrier, and the participants' eye movement and measured the horizontal illusory effect between two Gabor patches set in a vertically line. They concluded that the envelope-relative carrier velocity is the main influencing factor of the MIPS and that there is an asymmetry of effect if the envelope is also moving such that a carrier moving in an opposite direction induces a larger illusionary percept. This led the researchers to propose that the visual system interprets the prediction of position shift as less likely when it is toward the envelope's future direction on the retina.

2.2.1 Mechanism of MIPS

The causal processes underlying MIPS remain unclear despite considerable research conducted over the last thirty years (Park & Tadin, 2018). It has been argued that illusionary position shifts are manifestations by the mechanisms the visual system uses to compensate for the physical translation a moving object would have been displaced during the delay associated with visual processing. Some studies have suggested that the visual system corrects for neural transmission lags by extrapolating the future position of the target object on the basis of its velocity and neural latency (Yamagishi, Anderson, & Ashida, 2001). Indeed van Heusden, Rolfs, Cavanagh, & Hogendoorn (2018) in a recent experiment used the flash-grab effect to induce MIPS and showed that the latency of impending saccades predicted the perceived position of their target. They hypothesize that a neural extrapolation mechanism compensates for both visual and motor delays so that we perceive a moving object in the position that it will occupy by the time we have made an eye movement to it.

In their research discussion R. Hisakata, Terao, & Murakami (2013) proposed that a Bayesian approach could explain the MIPS effects they recorded in their experiments described above. Indeed, such an approach, which has been gaining recent success in predicting a variety of visual processes, is built on the premise that perception is best modelled as an inference that draws on sensory data and prior knowledge or expectation about the current state of the environment, based on Bayesian inference (Nour & Nour, 2015).

Such a method to interpret motion induced position shift and associated phenomena has been proposed that re-frames the coding of visual motion and position as an object-tracking paradigm (Kwon, Tadin, & Knill, 2015). The objective here is to develop a computational model that describes data culled from other psychophysical and physiological experiments that provide insight on the ‘how’ and ‘why’ rather than the ‘where’ of visual processes (Park & Tadin, 2018). In an ideal tracking system afferent position and motion signals are integrated with prediction data from the recent past to keep perceptual estimation of the position and motion of a target object constantly updated. Kwon, Tadin, & Knill (2015) propose that such a system underlies perceptual mechanisms and consequently linking position and motion in predictable ways. They modelled the system using a Bayesian framework that optimally uses sensory inputs to generate interferences about the sources of motion and position signals in the environment. The model includes two sources of motion – an object's translational velocity and motion of the texture within the object – while the observer is presumed to acquire noisy sensory inputs of the object position and the velocities of the object and of the texture pattern within the object boundaries relative to the retina. Computationally, the model can be realized as a Kalman filter (Kalman, 2011), a Bayesian algorithm that applies a weighting factor to sensory inputs based on their reliability over time (Park & Tadin, 2018). Stated simply, when the current sensory signal is well-defined historical information is not useful but in high ambiguity situations, past data strongly affects perceptual prediction of object states. To resolve the attribution problem, the Kalman filter also optimally distributes responsibility for the retinal input of the object's internal texture movement to object velocity and pattern motion. When there is low uncertainty of position, for example when the stimulus is a drifting Gabor grating with stationary envelope and sharp aperture, the system correctly assigns the motion to the real source (local carrier motion) and little or no MIPS is perceived. However, when there is high uncertainty of position, for example a drifting Gabor patch with eccentric envelope and Gaussian aperture, the model attributes more of the sensed texture motion to the object motion. This is a reasonable inference given that global object motion predominates in experience. As a consequence, under these conditions perception is led to an estimation of position being shifted in the direction of motion (Kwon et al., 2015). These model predictions match experimental data and furthermore the model could accurately account for other perceptual illusions like the curve-ball effect and position-shift for rotating targets.

2.2.2 MIPS in Action and perception

An influential view in cognitive psychology has historically been inspired by a brain-as-computer analogy. This entails serial functioning by processing inputs (say perception), executing computations (cognition), and generating outputs (action). Such approach has helped drive the notion that perception and action are at opposite ends of a serial cognitive process implying that action is separate from perception (Witt, 2018). For most humans, vision is a vital means for executing effective actions (Marinovic et al., 2012) and so it is natural to regard visually guided actions as having been fashioned on the basis of our perception of the environment (Ueda, Abekawa, & Gomi, 2018). Indeed over recent years many theories grounded on views that action is a kind of perception, effects perception, or is itself an combined part of perception have been proposed. However, despite the phenomenology of an integrated visual experience, there are experimental indications that suggest visual signals are handled by two distinct pathways for one for processing perception and the other for action (Creem-Regehr & Kunz, 2010). These streams, both stem from in the primary visual cortex forming a dorsal pathway projecting to the posterior parietal cortex and a ventral path extending to the inferotemporal cortex. It has been proposed that not only are these two streams anatomically distinct but they also code functionally distinctive attributes of objects (Medendorp, de Brouwer, & Smeets, 2018). Mainly based on clinical cases of patients with a lesioned ventral pathway who could not satisfactorily report the orientations or dimensions of objects with which however, they could interact well and conversely, other patients who could not interact with objects because of a damaged dorsal pathway, but were able to make perceptual inferences about them, Goodale & Milner (1992) had consequently proposed that the two visual streams process similar properties, but for distinct purposes. Famously, they proposed the two visual pathways hypothesis where the ventral pathway is concerned with perceptual choices of awareness or recognition (‘what’) while the dorsal stream handles the use of visual sensory data about the same object characteristics for action or visuomotor control (‘how’) (de la Malla, Smeets, & Brenner, 2018).

Of interest is that the ‘what & how’ pathway model implies that perception is very susceptible to visual contextual illusions while actions are mostly illusion resistant. The rationale is that for perception, the ventral stream encodes objects’ properties allocentrically - that is relative to other objects – so logically will be highly sensitive to visual context. The dorsal stream however encodes sensory input for computations relative to the observer - that is egocentrically - so actions it indicates are assumed to be generally unaffected by contextual illusions (Medendorp et al., 2018). Resulting from this thinking, visual illusions have been used as stimuli in experiments to find supporting evidence for this functional dichotomy of the two visual pathways (de la Malla et al., 2018). For static inputs such as in the study of the effect on grasping of illusory size, there are several reports that actions are not shaped by perceptual illusions (Marinovic et al., 2012) although there is controversy about this and in other research findings when requirements for perception and action tasks were matched, both the action and perception were similarly affected by the visual illusions (Franz & Gegenfurtner, 2008). In research concerning moving objects like a drifting Gabor in a stationary envelope, visuomotor action tasks were found to be more (rather than less) susceptible to illusionary error than perceptual tasks (Yamagishi et al., 2001; Marinovic et al., 2012). However, again on re-examination of these effects, (Kerzel & Gegenfurtner, 2005) showed that depending on the experimental methodology used, divergent results for action and perception could be duplicated, overturned, or eliminated.

2.2.3 MIPS and saccades

Saccadic eye movements are deemed an elemental action as well as a perceptual mechanism (Herwig, 2015). Because of their nature, researchers have often opted to use saccades to investigate the influence of contextual perception illusions on visuo-motor processing – grasping or pointing are voluntary actions and their motion paths prone to visual feedback while saccades are ‘ballistic’ meaning that once they started, their trajectory cannot be changed mid-course by visual information (Medendorp et al., 2018).

In the context of a rotating grating illusion that elicits a MIPS percept, Zimmermann, Morrone, & Burr (2012) investigated if saccadic landing is also biased by this motion. Their findings indicate that the motion influenced both perception and saccadic landing to a similar extent and suggested these observations support the view that action and perception could use different reference frames to encode a common representation of object position. They also noted however that in their experiments stimuli were very brief which is rather uncommon in real life. This and most other studies examined saccades directed to static envelopes in a conventional MIPS or single-drift configurations having a stationary window with local pattern motion. However, a more recent study (Lisi & Cavanagh, 2015) utilised a double drift stimulus where there is a moving envelope containing internal orthogonal pattern motion. This is the stimulus that leads to the curve-ball illusion mentioned earlier and has the same basic characteristics of single-drift MIPS but leads to a stronger positional illusion by accumulation the shift over time. Lisi & Cavanagh (2015) found that while perception shows a large deviation in the apparent direction of motion, saccade landings show a negligible shift that is solely contingent on the instantaneous internal motion direction immediately preceding saccade onset. They hold that these results demonstrate a central dissimilarity between perception and action and that while percepts experience build up from prior sensory inputs, action appears to process only the newest visual data.

Recently Ueda et al. (2018) have questioned the temporal validity of these results as in the previous studies using double-drift stimuli, saccades were measured in an immediate manner whilst perceptual measurements were made without time-limit. They conducted experiments operationalizing temporal changes in the impact of double-drift MIPS on perception and saccades. The findings were that the illusion effect was contingent on the time allowed before saccades or perceptual choices, for both eye movements and perception.

Pointedly, the MIPS effect was small when saccade and perceptual localization was done immediately following the stimulus with saccades gradually shifting to the MIPS induced location as the elapsed time increased. The researchers suggest that these results imply that action responses and percept judgments are made on the basis of a common position representation that evolves in time over the course of integrating visual information (Ueda et al., 2018).

2.3 Alternative approach to 'what & how'

Rather than approaching the two visual streams hypothesis as dictating perception as being ventral pathway reliant and action as guided by the dorsal stream, an alternative interpretation of clinical and experimental data could be the proposal that the salient visual route for a visual task is established by the visual property that is of relevance and not if the task is a perception or an action. De la Malla et al. (2018) argued that if comparing the perception of an attribute that is not used in determining the characteristics of the action is why there seems to be a dissociation between effect of an illusion on perception and action, then one would not envisage a dissociation if the action is indeed dependent on the perceptual attribute with which it is contrasted. On this basis they conducted a study using a moving drifting Gabor envelope to test if intercepting this target at a fixated location is biased by the perceptual illusion. The results indicated that errors in interception were similar to the illusory changes in the perceived target motion. This is in contrast to what the two visual systems hypothesis as usually interpreted would predict (de la Malla et al., 2018) and reinforces the view that the dorsal pathway is all-important for motion processing be it to perceive or to interact with a target object (de la Malla, Brenner, de Haan, & Smeets, 2019). This is also in line with the general recognition of MT as a significant neural correlate of motion perception (Maus, Fischer, & Whitney, 2013).

2.4 Interceptive actions

Often day-to-day behaviour involves interaction with moving objects which frequently takes the form of an interception. Usually, the target object is tracked by directed gazing and a successful interception often involves synchronizing actions with predictions of future positions or times of the ‘collision’ with the moving object. So to intercept the target its velocity and position are object attributes to be considered which however as discussed earlier are both subject to be influenced by other visual factors like for example MIPS (De La Malla, Smeets, & Brenner, 2017). Systematic inaccuracies in the perception of position or velocity could result in comparable errors in interception (de la Malla et al., 2018).

In the section ‘Mechanism of MIPS’ above, it was mentioned that Kwon, Tadin, & Knill (2015) described a computational tracking model where position and motion signals integrated with prediction data from the recent past continuously update estimation of the position and motion of a target object. Aguilar-Lleyda, Tubau, & López-Moliner (2018) used such a model to predict the imports of visual signals in performance of sensorimotor interception actions on a moving target. Such actions are planned by distributing reliance between temporal and spatial information to achieve a specific result and performance. For example, this position-motion coupled model predicted that for short motion durations speed estimations would be more uncertain and in such a situation, the model weight the distribution towards using spatial information for action planning. Although the proposed model has limitations, its predictions confirmed empirical results and showed that a single position-tracking mechanism could provide a unified computational explanation (Aguilar-Lleyda et al., 2018).

2.5 Processing motion in three dimensions

It is quite remarkable how the world is perceived as a three dimensional construct when visual sensory inputs on the retina are essentially two dimensional. Indeed this geometric ambiguity known as the inverse problem is created because of the transformation of source data from 3D to 2D to produce the proximal stimulus cannot then uniquely determine the properties of the distal image (Soon et al., 2017). Nonetheless, an observer typically sees only one three dimensional object and the percept often correctly defines the physical target. An extensive body of work suggests that the human visual system obtains and uses past experiences of the properties that depict the distal stimulus to compensate for the information that cannot be known directly (Pizlo, 2001). This strategy uses cues to build the most probable visual percept.

Research has identified a number of ways how visual motion aids in 3d perception. The visual system can utilize possible binocular cues for depth motion such as variations in horizontal binocular disparity and in interocular velocity difference. The former refers to relative changes in retinal location and the latter to the similar direction but varying speeds in retinal motion of stimuli in the two eyes (Nishida, 2011). Here, the visual system leverages on the point that dissimilar signals in each eye are created by motion in depth and studies have indicated that these cues could be handled by separate processes that are implicated in treating 2D motion (Park & Tadin, 2018). Another visual cue relates to when an observer makes head-movements the retinal motion of stationary objects in the scene off to the side of the fixation point also move. Closer objects will cause retinal motion opposite to the direction of head movement but far-off objects will seem to move in the same direction. Moreover, the speed of motion on the retina will be the slower the farther away the object is. This phenomenon is known as motion parallax and it is an important depth cue for closer objects but efficacy decreases with distance (Renner, Velichkovsky, & Helmert, 2014).

A third cue of visual motion to 3D perception is the large pattern of global motion that produces an optic flow field on the retina when there is egocentric movement through the environment (Nishida, 2011). For example, when an observer moves along a straight trajectory in a specific direction, the optic flow field radiates out from a point in the vista called the focus of expansion. Under such conditions, observers are remarkably accurate at perceiving heading. But this estimation becomes complicated if there is additional angular rotation due to say rotating head or eye movements. Here, estimation of heading by locating the focus of expansion would result in a bias away from the veridical trajectory direction. Known as the rotation problem this requires the visual system to disambiguate the causes of retinal motion to determine heading correctly (Burlingham & Heeger, 2018). Another problem related to optic flow mechanisms concerns how the visual system allocates the detection of object movement during self-motion. It must ascribe local motion vectors in the field to a moving external body or to the observer's motion or to both, for example walking through a corridor the observer has no percept that the corridor walls are in motion but that it is stationary and the movement is ascribed to self (Warren & Rushton, 2009).

In the context of the current study, 3D motion is of particular interest especially the aspect of its simulation in a virtual environment. Underlying theoretical aspects of this topic will be further expanded in the discussion section.

2.6 Present study

Researchers and theorists have over the years attempted to explain how the visual system enables successful behaviour in the world when the visual attributes of physical sources in the environment are not perceived as specified by retinal images (Soon et al., 2017). Although the capacity to infer the spatial position of objects enables observers to effectively engage in visually guided actions and allows for self-navigation through a three-dimensional environment however, as discussed previously, accurate determination of position is much reliant on the nature of the stimulus. Temporally, humans are able to accurately interact with swiftly moving objects even though awareness of visual events lags behind the occurrence of those events in the world because of neural latency (van Heusden et al., 2018). Indeed, visual illusions abound as examples of how "perceptual errors seem to reveal a rational (but automatic) perceptual system designed to correctly interpret the retinal images evoked by the world" (Geisler & Kersten, 2002, p. 508). Researchers have taken advantage of visual illusions evoked through appropriate stimuli to study underlying visual mechanisms. As previously discussed, selective findings that visual illusions affect perception but not actions has provided significant backing for the two visual systems hypothesis (Kopiske, Bruno, Hesse, Schenk, & Franz, 2016). Typically effects of an illusion on perception are compared to the effects on action in separate experiments however “the comparison between perceptual and motor measures depended strongly on the methods used” (Kerzel & Gegenfurtner, 2005, p 191).

Combining effects of illusionary shifts and action together is mostly seen in tracking experiments. One such example is a combined measure used by Caniard et al., (2011) where the task was for participants using a joystick, to move an internally drifting Gabor patch envelope moving in an orthogonal direction, continuously centring it along a randomly curving path. They found that for right local drifts participants adjusted the patch global position of to the left of the path and left drift adjustments were to the right. These errors and other experimental data followed known perceptual position-shift induced errors and showed that in this case action was not immune to the illusory effect. In a later study (Caniard, Bülthoff, & Thornton, 2015) investigated MIPS with an ‘active task’ and ‘passive task’. In the former, using a computer game format on a tablet computer, participants actively controlled an internally drifting Gabor’s global position horizontally in order to guide it through the centre of a number of ‘gates’ as the Gabor envelope moved in a vertical direction. In the passive task, participants were shown the same scene but they could not control the patch but rather recorded left or right error judgements as the patch was guided by automatically over a variable trajectory. Again the findings were that active position control of the Gabor did not eliminate errors induced by MIPS but indeed the size of the effect was greater than in the passive task.

The present study investigates how humans interact with objects in motion notwithstanding that perception is widely influenced by visual illusions. Specifically it further explores the influence of motion-induced position shift during active perceptual tasks. The goal is to take the ‘game’ experimental paradigm from a flat two-dimensional setting and study the effect of active control in a simulated 3-dimensional environment thereby reflecting a more ecological ambiance for the experiments. The study comprises two experiments – the first requires participants to control the stimulus to centrally follow a line on the floor of a randomly curving corridor; in the second experiment involves participants in steering the stimulus to intercept the midline of horizontal blocks strewn in random positions on the floor of the corridor. The intent was to measure and analyse the effect of action under globally moving but locally static or drifting visual stimuli in a virtual three-dimensional environment.

2.7 Motivation

There are several motivators for the present study. Firstly a basic research goal is associated with furthering understanding of the functional organisation of the human visual system. Of particular relevance is to advance knowledge about interactions between motion perception and action. In contrast to real-world object motion, much of basic motion research has been centred on static stimuli that contain local motion but no global changes in position. Recent experimental work and computational modelling has however advanced the view that motion and position are two implicitly linked and inextricable properties of visual stimuli (Park & Tadin, 2018; Kwon et al., 2015). Likewise, more conducive to our understanding of the interactions between action and perception may be the reinterpreting the two visual pathways concept as arising from the difference between a path tightly linked to cortical regions that direct our actions where visual attributes for action are processed and another neural path for object recognition and less directly connected to these areas (de la Malla et al., 2019).

The second motivator is of a more pragmatic nature and concerns practical implications of the present study. In day-to-day and professional environments, people are frequently required to make judgements about what actions to execute based on what they see. Safety research recognizes the critical role of perception and how perceptual visual biases influence this choice of action (Wickens, 2014). Action effects of perception have been recorded in an extensive variety of tasks and situations. In aviation for example, visual illusions are known to bias the perceived on-approach visual angle making the runway to appear higher or lower than it really is which has a bearing on aircraft landing decisions (Witt, Linkenauger, & Wickens, 2016). A survey of U.S. Army AH-64 Apache helicopter accidents for the period 1985 to 2002 reported 228 accidents. 41% of these involved the Apache's helmet mounted display (HMD) with motion illusions being the most frequent causal factor in all of the accidents studied of which 24% were related to illusory drift (Temme, Kalich, Curry, Pinkus, & Lee, 2009). This suggests the crucial need for designs to account for how visuomotor-guided actions are generated by the visual system and how it is affected by visual illusions. The role of smart and human interactive technologies is becoming more widespread - active controls requiring visuomotor interactions with head-up, augmented reality displays or navigation displays where global perception of position and local dynamic data are intentionally overlaid have become quite common. Therefore research that sheds some understanding on how human-machine interactions in the presence of local motion can be designed such that unsafe outcomes can be predicted, avoided or eliminated has practical merit (Caniard et al., 2011).

In a typical perception experiment, participants are considered by design as passive observers or minimal actors in the lab environment viewing brief stimuli often from a stationary perspective of a frontoparallel plane. It is argued that constraints on stimuli and participants isolates the perceptual data being studied however the drawback is that the experiment lacks ecological substance (Scarfe & Glennerster, 2015). The third motivator for the present experiment is to conduct a study using a simulated three-dimensional environment and designing the experiment as an interactive game which participants can 'play' naturally without any pressure because experimental data is collected from their monitored and recorded movements respond. Hopefully, “the experiment would no longer ‘get in the way’ of what the person is doing, and we would begin to study how sensory systems respond naturally in everyday life, rather than in the contexts of the experiment itself” (Scarfe & Glennerster, 2015, p 8). To use this research paradigm however requires understanding and custom manipulation of software in order to create an engaging reality simulation which leads to the fourth motivator and it is really the corollary requirement of the third.

Many experiments in cognitive psychology and neuroscience utilize software that controls against an accurate timeline, stimuli presentation to a participant, senses and records responses, and registers events for future analysis. However, most of the commonly used suites are lacking adequate 3D graphics support required to build, for example, animated three dimensional environments (Del Grosso & Sirota, 2019) as required for the present study. The Unity3D game engine (<https://unity3d.com/>) was used for this development. Besides serving as a means to an end, this was also an opportunity to gain experience of this game-engine’s possibilities and limitations as a research tool. Although to-date Unity3D is one of the foremost game development environments, it has been little used as a tool in cognitive and neuroscience science experiments although it has been gaining attention over the last two years in this field (Del Grosso & Sirota, 2019; H. Zhao et al., 2018; Veto, Uhlig, Troje, & Einhäuser, 2018; Laitin, Tymoski, Tenhundfeld, & Witt, 2019; Spanlang et al., 2014; Weibel et al., 2018; Harjunen, Ahmed, Jacucci, Ravaja, & Spapé, 2017; Vasser et al., 2017).

3 Methodology

3.1 Overview

The general aim of the present study is to explore the influence of an illusory visual motion-induced position shift on active perceptual tasks. Specifically the research examines this effect of active control in a simulated 3-dimensional environment created by developing a bespoke game-like format using the Unity3D software suite. Unlike most previous studies that have rendered experiments in a flat two-dimensional setting the current study attempts to reflect a more ecological setting for the experiments. The study comprises two experiments – the first is a tracking task that will be referred to as ‘Centre-Line Following’ and the second experiment is an interception task to be referred to as ‘Waypoint Collision’ – both using a Gabor patch stimulus, the intent being to measure, analyse and compare the effect on active steering under globally moving but locally static or drifting visual stimuli in a three-dimensional environment. This section will provide details about the participants, equipment, stimuli and experiment procedure as well as a review of the process to build the virtual environment.

3.2 Participants

A total of 14 participants with an age range of 20 to 47 (M_{age} = 28.6, SD_{age} = 8.58) took part in the study - 10 of the participants were female, 10 were right-handed and all had normal or corrected-to-normal vision. The participants were a convenience sample recruited from the University of Malta student and alumni communities and gave written informed consent before taking part in the experiment. They were naïve as to the aim of the research and were free to withdraw their participation at any time.

The study was conducted in conformance with the Ethics and Data Protection guidelines of the University of Malta and ethics approval was obtained from the University of Malta, Faculty of Media & Knowledge Sciences Ethics Committee prior to commencement of the experimental sessions. There was no financial remuneration for participation.

Sample size was determined before starting data collection and was based on two approaches. We could not find documented quantitative estimates of effect sizes in previous experiments that specifically used a similar stimulus as in the present study. However, the drifting Gabor illusion is often referred to as a ‘robust’ illusion so it was considered reasonable to assume a strong effect size ($\eta^2 = 0.14$). To calculate the required sample size the software G*Power Version 3.1.9.4 (Faul, Erdfelder, Buchner, & Lang, 2009) was used.

Assuming an effect size of 0.4 (Cohen f), alpha of .05, required power of .8, one group of participants, and three measurement conditions (stimulus internal drift to left, to right and static), the *a priori* power analysis for a repeated measures statistical test suggested a sample size of 12 subjects. This would be a rather conservative figure because in this study, as is typical in much cognitive science research, multiple observations per participant per condition would be recorded which is known to increase the effect size but is not covered by most power calculators (Brysbaert & Stevens, 2018). Indeed a way to increase the power of an experimental design is to increase the number of observations per condition rather than the number of participants (Brysbaert, 2019). Westfall, Kenny, & Judd (2014) provide a web-based power application to assist in planning experiments in which a sample of participants responds to a sample of stimuli. Using this on-line application (jakewestfall.org/power/) and solving for the number of participants for a 'stimuli-within-condition' design, effect size of .6 (Cohen d), total number of stimuli per participant 160 and a target power of .8 indicates a minimum number of participants of 12. Generally, the a priori sample size estimate of 13 participants was supported by both power calculations.

3.3 Equipment

The experiments were conducted in a sound-proofed booth with no sources of illumination except from a 40" inch LED colour display, 16:9 aspect ratio with a 1920 x 1080 pixel resolution, on which the simulated three-dimensional environment was presented. Participants were seated directly in front of and at approximately 110 cm from the monitor. Head and eye position were not monitored or constrained and from that position the display subtended a horizontal visual angle of 46˚. The experiment was presented and controlled by a custom built application running on a Mac Mini machine with a dual-core Intel i5 processor, Intel HD Graphics 4000 and OS X 10.12.4 operating system. The participant could interact with the application via keyboard, mouse or joystick connected to the computer's USB ports. The joystick was the principle device used by participant to control the stimulus. Moving the stick left or right would correspondingly move the stimulus and point of view in the displayed environment. The setup is shown in Figure 2.

3.4 Stimuli

The target stimulus acted on by the participants in this experiment was a low-frequency Gabor patch. These stimuli have some benefits for experimentation of visual phenomena. Gabor patches are Gaussian-windowed sinusoidal gratings produced by sinusoidal luminance defined waveforms and named after Gábor Dénes, who explained specific advantages of their mathematical form. It was shown that these gratings minimized uncertainty of stimulus localization in the spatial frequency and visual space domains simultaneously. This mathematical characteristic is a theoretical motive for using Gabors in motion perception experiments as it allows dissociation of the stimulus motion from the stimulus location (Fredericksen, Bex, & Verstraten, 1997). Additionally, studies have

Figure 2. Experiment setup showing display and joystick

suggested that striate cortical neurons operate as approximate linear spatial filters emphasizing their sensitivity to the spatial frequency of these sinusoidal grating patterns (Movshon et al., 1983). Also this stimulus is well-suited to investigating the effects of MIPS because the position shift resulting from drifting Gabors is continuously present (Kosovicheva, Wolfe, & Whitney, 2014).

The general luminance function for a horizontally drifting, vertical Gabor grating enveloped by a circular Gaussian window is:

$$L(x, y, t) = L_m \left\{ 1 + C_p \, cos[2\pi x f_c + 2\pi f_t t + \phi] e^{-\frac{(x^2 + y^2)}{2\sigma^2}} \right\}$$

where L_m is the mean luminance of the display, C_p is the peak contrast of the Gabor which for the experiment was always at maximum contrast and equal to 1, f_c is the grating spatial frequency and was kept the same for all conditions at 1.6 cycles/°, and σ the standard deviation of the Gaussian envelope (Fredericksen et al., 1997). This was set to 0.5° (17 pixels) and the value of the Gaussian function considered zero for all points more than 3 standard deviations from the centre giving a visible spatial extent (VSE) of approximately 3.1°. f_t is the temporal frequency or local drift of the grating which was retained at 1.6 cycle/s to the right or left across conditions as appropriate. ϕ is the phase shift of the sinusoidal carrier which under static carrier conditions took any random value of the twenty possible angles between 0° and 342° in steps of 18°. The order of application of these was randomised separately for each participant.

For this study the Gabors were created using an online Gabor-patch generator (https://www.cogsci.nl/gabor-generator) specifying an orientation of 0°, size of 100 pixels, a Gaussian envelope with standard deviation of 17 pixels, a spatial frequency of 0.05 cycles per pixel, transparent background and black and white gratings for maximum contrast. Twenty images were created, each 18° phase-shifted from each other to cover a complete cycle. An example is shown in Figure 3. These were processed in an image manipulation program, GIMP 2.10.8 (https://www.gimp.org/) to create a spritesheet which was imported into Unity3D and used to generate the stimulus objects. The Gabors were ultimately deployed as animated sprite objects in the Unity3D application (details discussed in section 3.5.4).

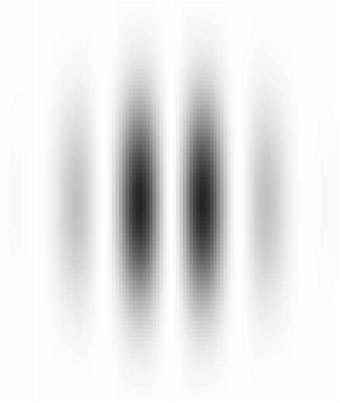


Figure 3. Example of Gabor patch used in experiment

The stimulus was setup in the 3D environment such that it is always immediately in front of and fixed relative to the participant’s point of view. The stimulus (and participant) moves forward at a simulated velocity of 6m/s and can be steered to the left or right in the frontoparallel plane, orthogonally to the global motion direction.

3.5 Custom Application – the environment

As has been stated elsewhere (Del Grosso & Sirota, 2019), most of the current popular software tools and libraries used in cognitive science experiments are missing comprehensive 3D graphics support that is needed for a wide range of visual perception experiments, such as 3D virtual reality environment builds. However, to this author’s knowledge there are at least two accessible, open-source frameworks that facilitate the structuring, executing, and evaluate of experiments in a 3D virtual reality (VR) environment. The goal of these frameworks is to enable experimenters to focus more on research issues and less on the practical applications and tooling for the study. One of these frameworks, EVE (Experiments in Virtual Environments), was originally designed to support spatial cognition and navigation studies (Grübel et al., 2017). The second is Virtual Reality Experiments (VREX) Toolbox , narrowly focuses on creating indoor VR environments for change blindness and false memory experiment types (Vasser et al., 2017). Although these applications were considered, it was felt that they did not provide sufficient flexibility to enable the environment required for the current study. Both EVE and VREX are based on the Unity3D game engine and for the current study this engine was also used.

3.5.1 Unity3D application

Unity3D is a popular cross-platform game creation engine developed by Unity Technologies (San Francisco, United States) that manages the graphics and physics engine underlying video game applications. The engine offers a primary scripting interface in C# programming language (Microsoft Corporation, Redmond, Washington, U.S), as well as a drag and drop user interface functionality. Version 2018.2.10 was used to build the application for the current experiment.

The experiment environment took the form of a ‘game’ played in an active first person mode. The participant takes this role, steering a ‘vehicle’, the nose of which is the Gabor stimulus. The action takes place as the vehicle moves forward at a constant speed through a curving corridor or tunnel. This was concept was inspired from an online tutorial (https://catlikecoding.com/unity/tutorials/swirly-pipe/) which was used as a basis but significantly amended and developed for the purpose at hand. The vehicle and hence the stimulus would move forward in depth always normal to the frontoparallel plane unless steered sideways (horizontally) by the participant moving the joystick in the appropriate axis. A flow chart showing the application protocol followed in creating the application is shown in Figure 4. Considerable effort and time was spent to create this Unity3D experimental tool which was a major task in this project and in the next section the development process will be described in some detail. It is to be noted that in Unity there are two types of views – a ‘scene view’ which is what the developer can see to manage application development and a ‘game

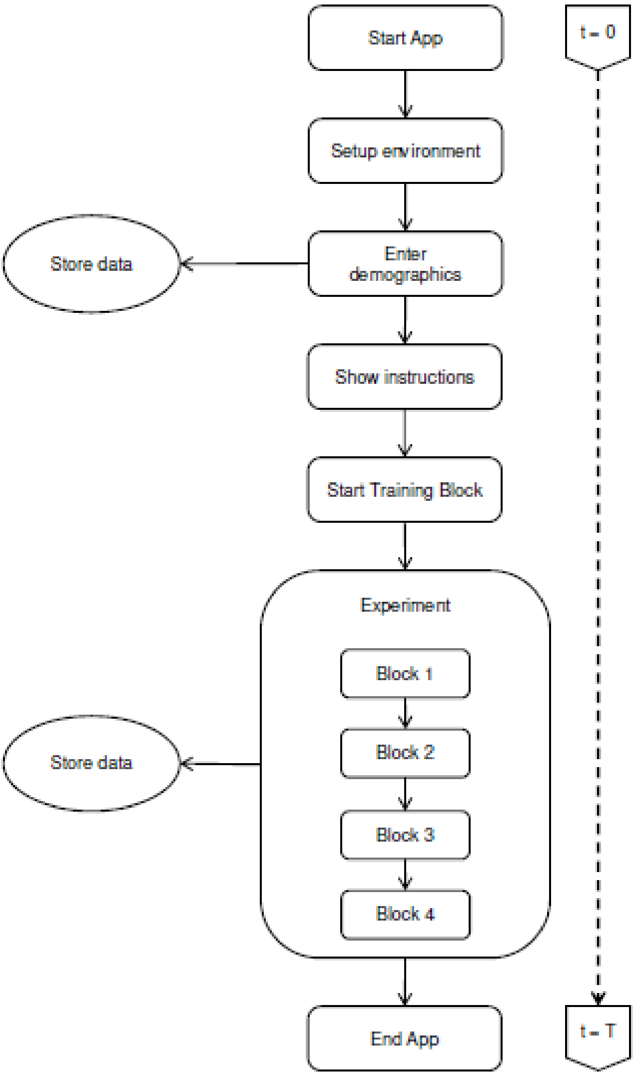


Figure 4. Application flow

view' which is what is presented to a participant during game play. Unless otherwise indicated all views depicted below are scene views.

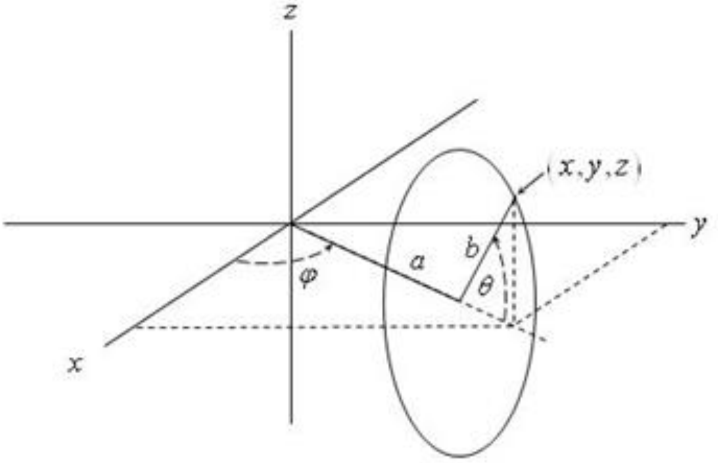
3.5.2 Developing the tunnel

The tunnel was developed using a system of pipes formed from circular torus sections. A circular torus can be described parametrically by the following set of equations.

$$x = (a + b\cos\theta)\cos\varphi$$

$$y = (a + b\cos\theta)\sin\varphi$$

$$z = b\,sin\,\theta$$



where θ is the angle around the pipe and φ is angle along the torus segment, a is the distance from the centre of the tube to the centre of the torus and b is the radius of the tube. The torus or part of is formed by fixing a and b and sweeping θ and φ from 0 to 360° for a full torus. A way of creating surfaces in Unity3D is by using mesh grids that layer a texture onto mapped vertices of the object. Quadrilateral surfaces of the mesh extend around the pipe (pipe segments) and along the pipe (curve segments) as shown in Figure 5 – the more segments there are the smoother the surface. In this case a square-sectioned tunnel was required so the pipe segments were fixed to four while the number of curve segments was parametrized so that it can be changed

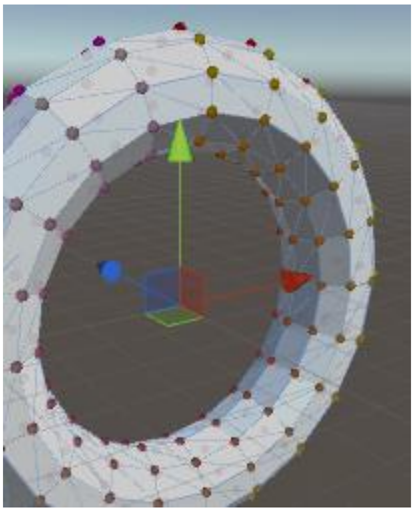


Figure 5. Mesh grid on torus

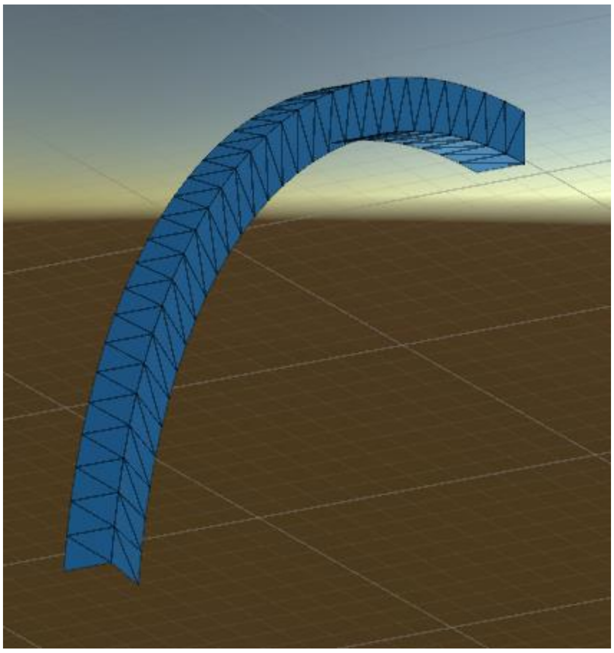


Figure 6. Single pipe section

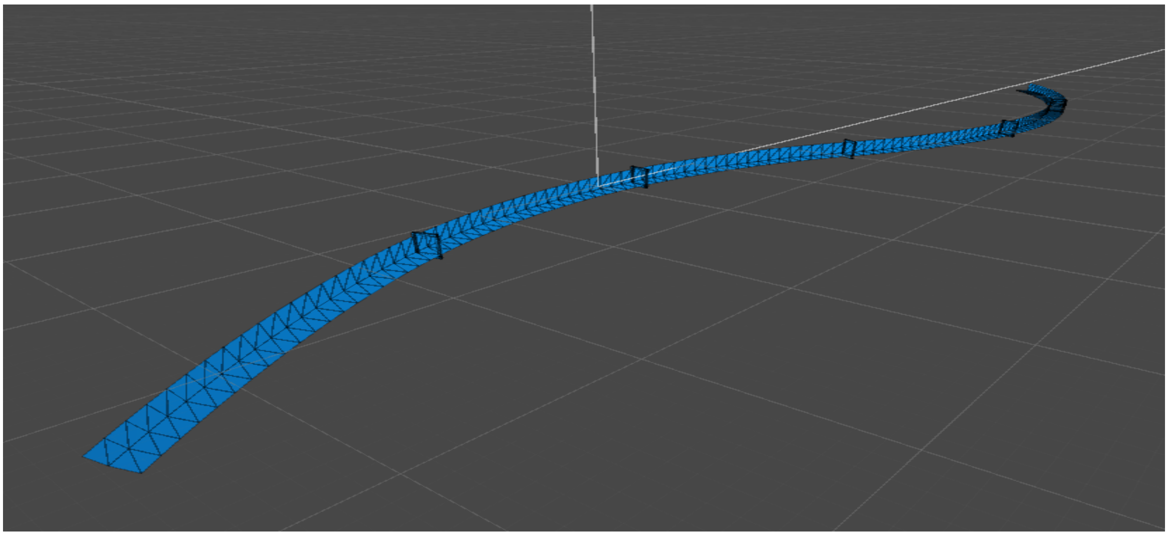


Figure 7. Pipe system made up of pipe objects

through code according to the experimenter’s needs. A single segment of such a pipe as used in this experiment is shown in Figure 6. This pipe was stored as a Unity prefab asset which essentially will act like a template used to create new instances of the same object in a scene. The game required an curving tunnel environment which could be built up by joining together these pipe instances. A pipe-system object was created to hold the instances of the pipe prefab that were generated.

There were two game requirements that needed to be controlled through code attached to the pipe-system object. Firstly that pipe sections would only curve to the right or left relative to the pipe-system and that pipes are generated on-the-fly; as the player passes one section a new section is generated, aligned and added to the end of a pipe-system object. The number of pipe sections visible in a scene was parameterized and the left or right direction of consecutive pipes was randomized so participants would not habituate to any particular curve pattern. A Unity scene view of the pipe-system is shown in Figure 7.

3.5.3 Targets and obstacles

Two experiments were created each as a separate build and using this pipe-system object and common C# code. In one experiment, the Waypoint Collision task, rectangular blocks were placed at random positions on the floor of the pipe with their long edges normal to the end of the pipe (and the direction of movement of the player through the pipe). In depth the blocks were always at the start of a pipe segment, however laterally they were placed at any random position between the pipe walls as seen in the scene view Figure 8. These blocks were generated as prefab instances child objects to the pipe object which in turn was a child of the pipe-system in an arrangement that is typical of Unity3D hierarchical object structures. The centre point of each block acted as collision target for the participant’s stimulus. The centre was marked by a white line to reduce target ambiguity for participants as the distance between this target and the actual point of collision with the block was the measured error. Additionally passing a block marked the count of a trial for the system. Figure 9 shows a scene view with a block placed at the start of a pipe section (outlined in orange) and having a white vertical line on its forward face to indicate the central target.

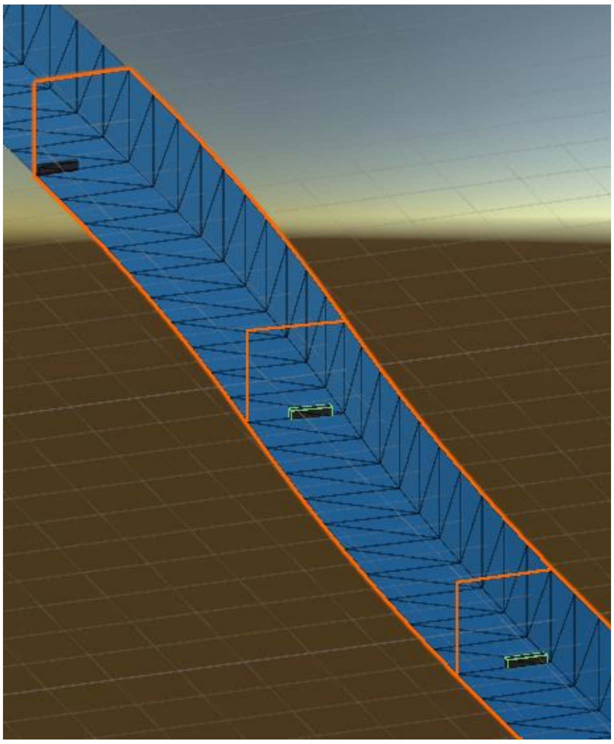


Figure 8. Lateral random placement of blocks

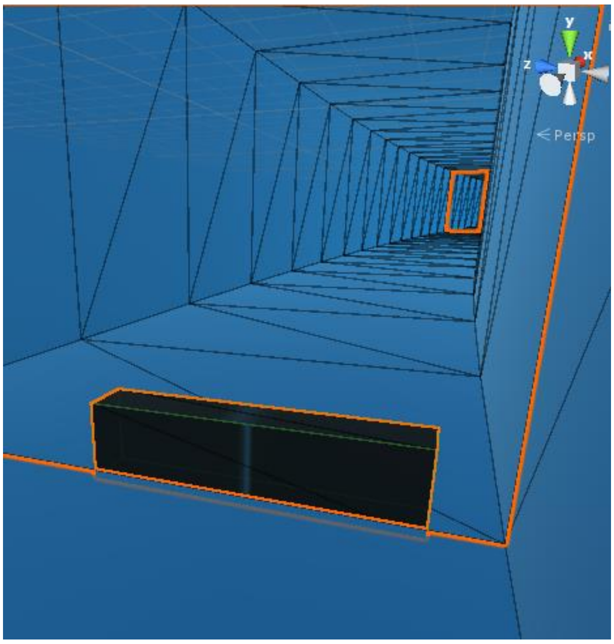


Figure 9. Block with white centre line mark at start of pipe section

In the other experiment, the Centre-line Following task, a centreline was created on the pipe's floor that followed the curvature of the pipe system. The participant was required to steer the vehicle to stay on the line. The line was created by applying a texture material shown in Figure 10 in a repeated wrap mode to the mesh grid quads that made-up the floor of the pipe and would automatically follow the curvature of consecutive pipe segments. The important factor, which was controlled by code applied to the pipe-system object, was that since pipe instances were aligned left or right after being created, the texture would always be applied to the bottom, floor mesh grid. Two vertical columns marked the beginning of a new pipe section. These had no involvement in the task itself but simply served to enhance the looming and optic flow effects and also served as a trial counter in the control software. The game views seen by the participant in these two cases are shown in Figure 11 and Figure 12 respectively.

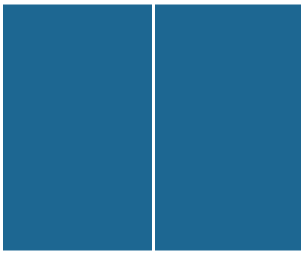


Figure 10. Pipe floor texture material in Centre-line following task

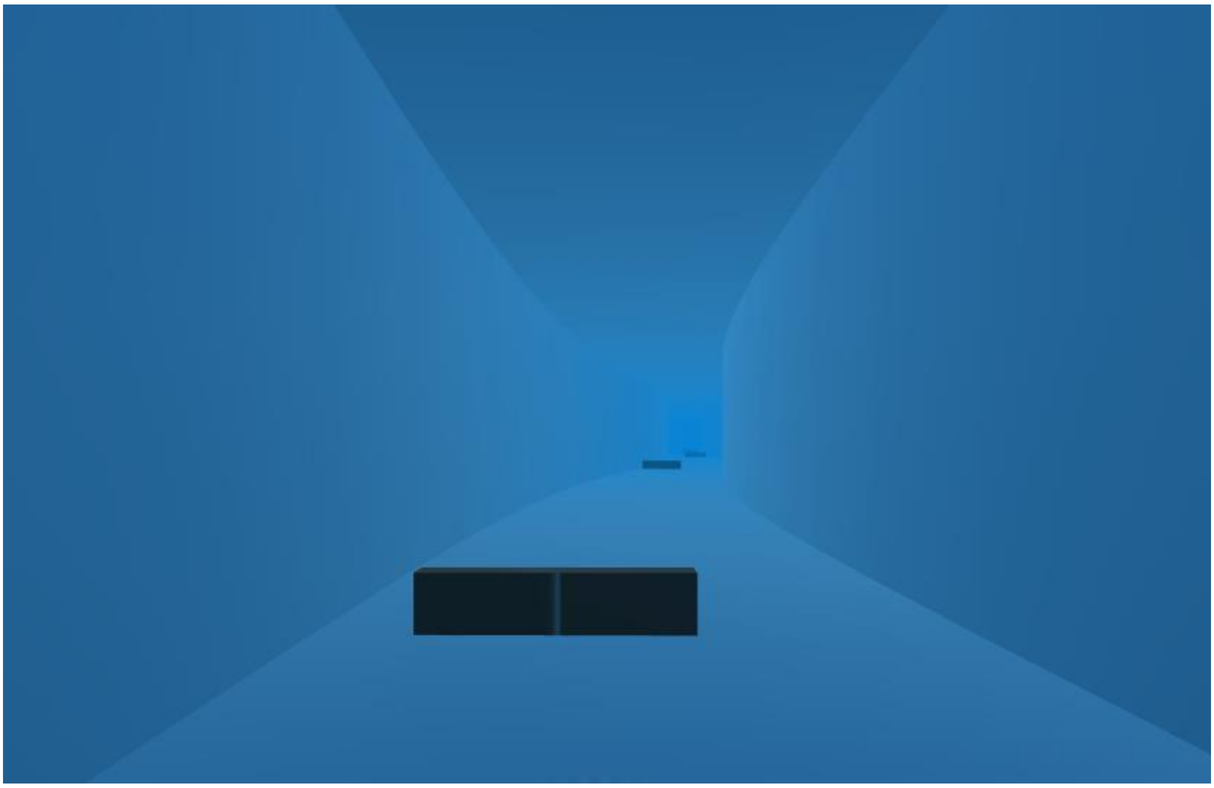


*Figure 11.*Waypoint Collision task tunnel environment

3.5.4 The stimulus

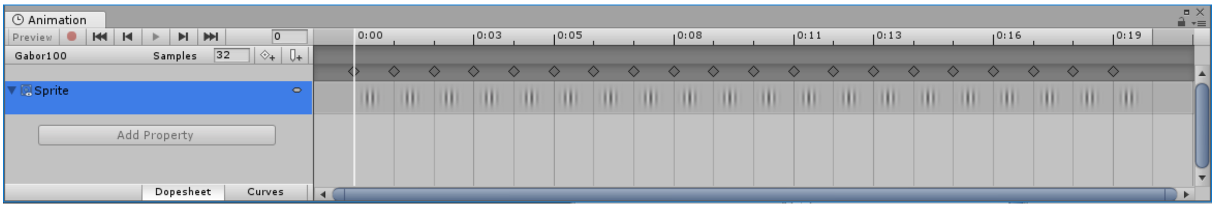
In section 3.4 above mention was made of the spritesheet created with GIMP that contained 20 phase shifted Gabor gratings. This was imported into Unity3D's built-in sprite editor to create a sprite object containing each of the 20 Gabor images. Sprites are 2-dimensional graphic objects. In this case using Unity3D's animation system, the 20 Gabor images are played sequentially to create an animation clip. The temporal frequency f_t which is the local drift of the grating was required to be 1.6 cycle/s to the right or left. Since there were 20 images in one cycle this temporal frequency was achieved by setting the sample rate in Unity's animator to 32 frames per second $(20\ frames\ \times 1.6\ cycles/s)$. The animation window is seen in Figure 13. A Gabor stimulus object was created as a child of the player

Figure 12. Centre-line Following task tunnel environment

object and had the animation asset added as a component to it. In experimental drift conditions the animator component would be activated through code and direction of drift also controlled by code simply by flipping the Gabor 180° around the axis along the pipe.

3.5.5 The player

The illusion of forward movement and pipe bend direction was created by the looming objects in the pipe and by the optic flow generated by moving the pipe's x-y plane



Gabor100

Samples 32

Figure 13. Unity animation window

orthogonally towards the player at a constant velocity. So the player object was kept at the origin and only the pipe system moved instead. An important function of optic flow is as an aid to estimating self-motion direction. Also observers' sensitivity to looming-like changes in scene object sizes can process looming automatically and accurately to approximate the rate of expansion of a scene separately from cues in the optic flow (Park & Tadin, 2018).

A player object was created to simulate the participant in the first person. Consequently, a camera object attached as a child object of the player would act as the player's 'eyes' though which the participant will view the game. The player object was positioned on the floor of the pipe and the Gabor stimulus was at the same relative position to its parent object. To enhance the first person view the camera object was positioned behind and slightly higher than the player and therefore the Gabor. This gives the feeling of overall player control on position in the pipe and for the participant the stimulus seems as an extension of the self. The typical participant's game view during an experiment is shown in Figure 14 within the border of the display and subsequent movement in the tunnel appearing similar to the view inside the windscreen border of a vehicle in motion.

Whilst the position of the patch relative to the display was fixed in the bottom middle the player's lateral position in the pipe could be changed by two factors. Firstly the physics of motion and the geometry of the pipe so that all things being equal the player would continue moving tangentially to the bend in a straight line until constrained by a pipe wall. It would thereafter continue to follow the wall until the pipe bends in the opposite direction. This action is controlled by code attached to the player object which computes the motion based on the angle of curvature of the current bend and the forward velocity of the player. This motion is the primary factor that deviates the player from the centreline of the pipe and renders a realistic trajectory. The second way the player's position could be altered is by active joystick control by the participant. The joystick inputs were configured in the code to move the player left or right at a fixed sensitivity. This movement is constrained by the pipe walls beyond which no lateral movement is possible. In the object code the player's resultant translation vector is calculated from the three velocities – the fixed forward velocity into the pipe, the lateral velocity due to pipe curvature and the lateral velocity due to joystick input –

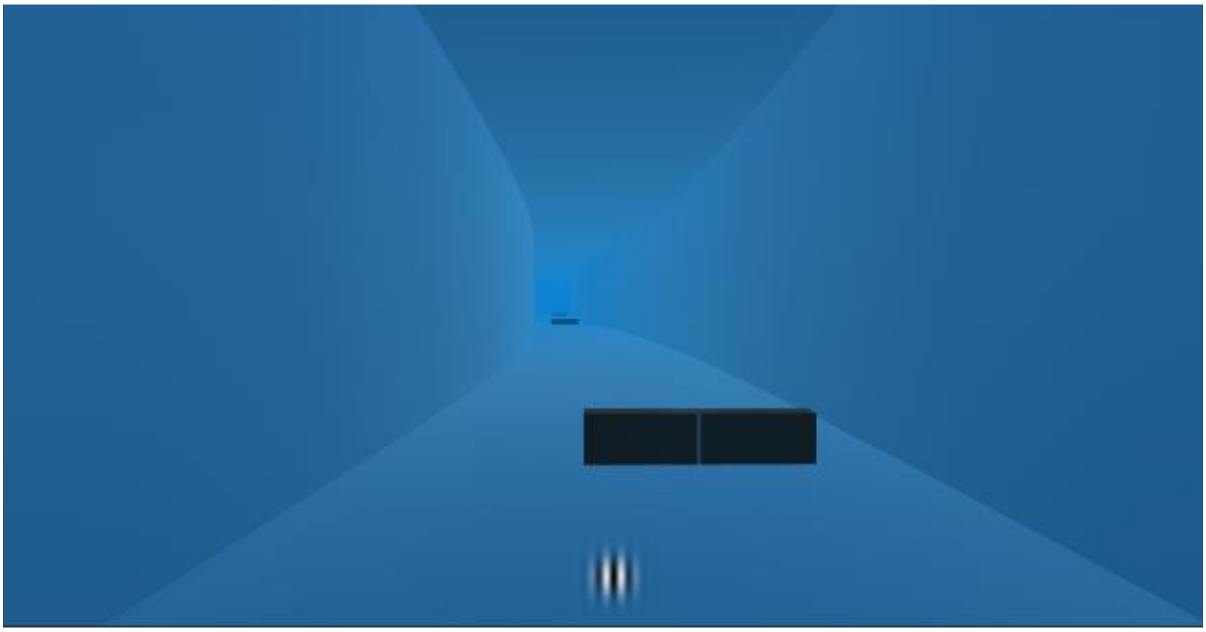


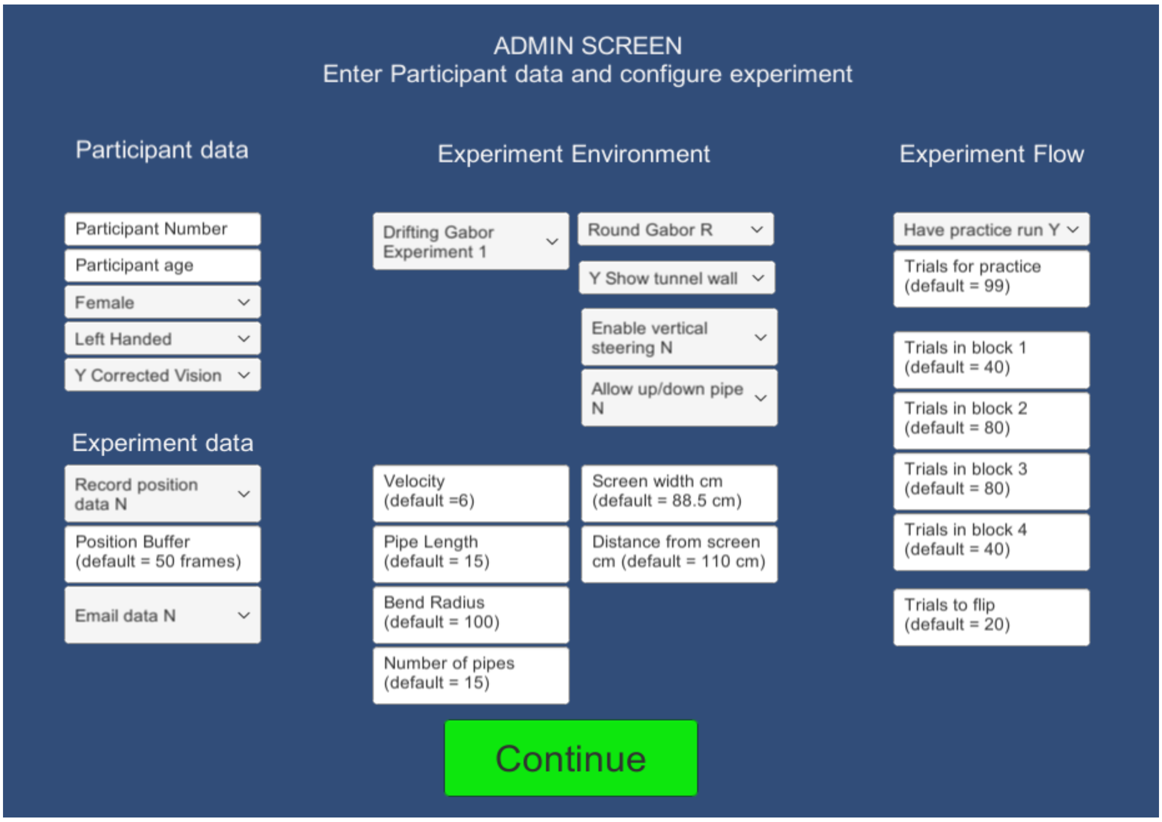
Figure 14. Stimulus inserted in environment as first person (participant) extension

every frame and the player position relative to the pipe continually adjusted. Because of the object hierarchy setup, movement of the player results also in equivalent motion of the Gabor stimulus and the camera object which for the participant appears as movement of the field of view inside the pipe relative to the participant's self. This enhances the 'first-person' illusion.

3.5.6 Scene management

The experiment flow was controlled by a user interface object and C# scripts that invoked one of four scenes, three of which were scenes that represented each experiment block and one that contained input boxes to configure the game and collect participant demographics and buttons to move the game to the next block or exit. Aspects of the environment, like pipe section radius and length and experiment flow variables such as trials per block were parameterized and could be changed through an administration screen that appeared on starting the application. Also it was possible to enter participant demographics at this point that would be automatically stored in a unique file on the system. Also captured with this data is information from the system regarding the display resolution and physical screen width and participant distance from screen entered by the experimenter in the administration screen. The programme records this data and also calculates the Gabor size in degrees of arc from the participant's position and also computes a factor to convert Unity3D units to degrees of arc in this setting.

Participant instructions are displayed on the next screen before starting a training block. The detailed administration screen with default parameter values can be seen in Figure 15.



ADMIN SCREEN
Enter Participant data and configure experiment

Participant data
- Participant Number
- Participant age
- Female
- Left Handed
- Y Corrected Vision

Experiment data
- Record position data N
- Position Buffer (default = 50 frames)
- Email data N

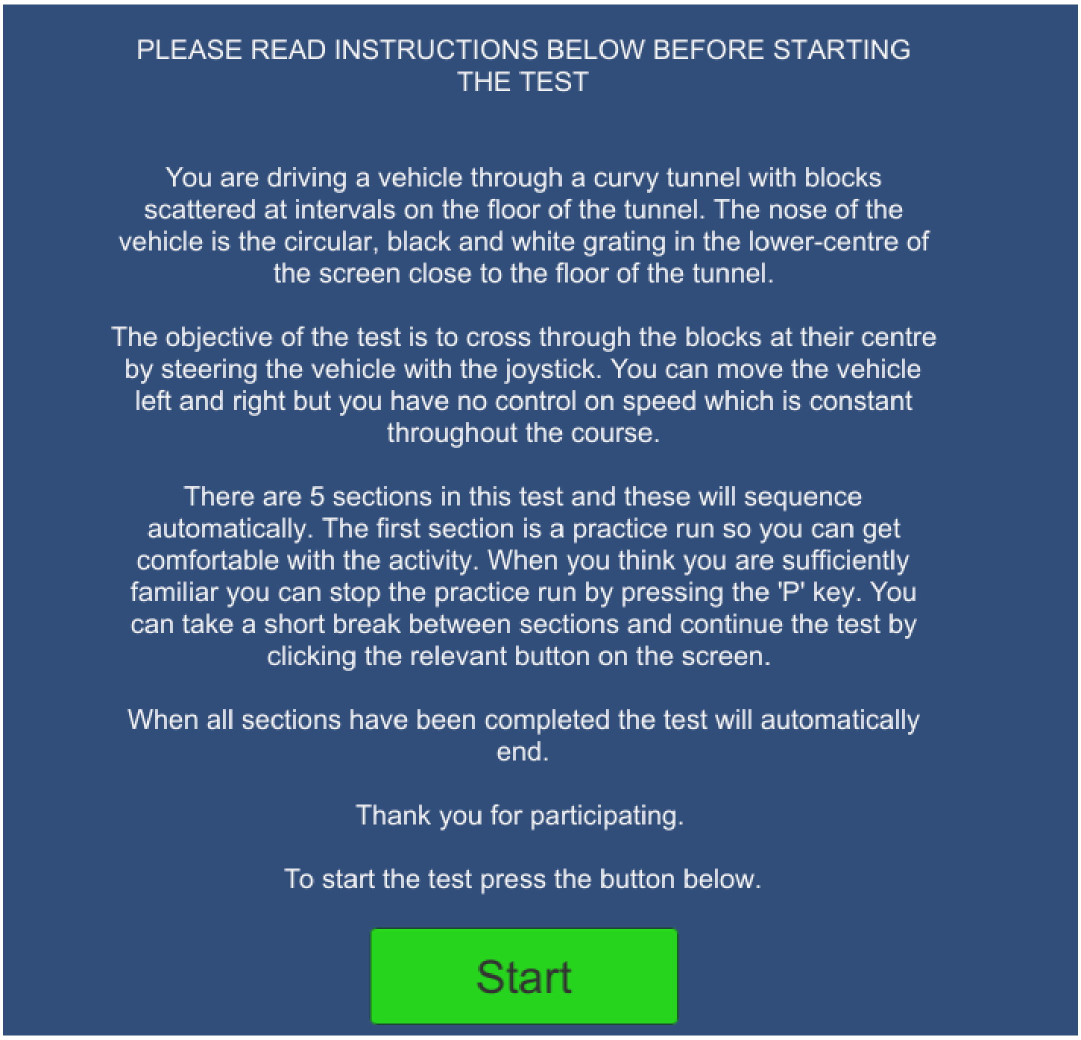
Experiment Environment
- Drifting Gabor Experiment 1
- Round Gabor R
- Y Show tunnel wall
- Enable vertical steering N
- Allow up/down pipe N
- Velocity (default =6)
- Pipe Length (default = 15)
- Bend Radius (default = 100)
- Number of pipes (default = 15)
- Screen width cm (default = 88.5 cm)
- Distance from screen cm (default = 110 cm)

Experiment Flow
- Have practice run Y
- Trials for practice (default = 99)
- Trials in block 1 (default = 40)
- Trials in block 2 (default = 80)
- Trials in block 3 (default = 80)
- Trials in block 4 (default = 40)
- Trials to flip (default = 20)

Figure 15. Administration screen

This is followed by an instruction screen which the participant reviews before continuing to the training block. An example of the screen for the waypoint collision task is shown in Figure 16.

The training block consisted of 99 trials with a non-drifting Gabor. Although not drifting the Gabor’s gratings were randomly set at one of the 20 phase shifted positions in the spritesheet. The training was intended to allow participants to become familiar with the task at hand and also with interactive and ergonomic aspects like speed, sensitivity of joystick and curvatures of the tunnel. The trial phase could be terminated by the participant at any time to move on to the main experiment. Although data was collected in the training part, it was not utilised at all in the analysis.



PLEASE READ INSTRUCTIONS BELOW BEFORE STARTING THE TEST

You are driving a vehicle through a curvy tunnel with blocks scattered at intervals on the floor of the tunnel. The nose of the vehicle is the circular, black and white grating in the lower-centre of the screen close to the floor of the tunnel.

The objective of the test is to cross through the blocks at their centre by steering the vehicle with the joystick. You can move the vehicle left and right but you have no control on speed which is constant throughout the course.

There are 5 sections in this test and these will sequence automatically. The first section is a practice run so you can get comfortable with the activity. When you think you are sufficiently familiar you can stop the practice run by pressing the 'P' key. You can take a short break between sections and continue the test by clicking the relevant button on the screen.

When all sections have been completed the test will automatically end.

Thank you for participating.

To start the test press the button below.

Figure 16. Instruction screen for Waypoint Collision task

Four blocks of experimental trials followed with various stimulus conditions as will be detailed a later section. The first and fourth blocks were no-drift conditions and were represented by the same scene. When the participant selected to move to these blocks the underlying code activated this particular scene with the Gabor object animator off so the sprite is static and rendered at random in one of 4 possible phase shifts – 0°, 90°, 180°, 270°. After 20 trials another random phase angle would be applied. This was done to counterbalance any effect which phase could have on the participant’s performance.

Blocks 2 and 3 were represented by two differently coded scenes. In both, the Gabor was drifting but the initial drift direction of the epoch sequence was different; one scene was coded to start with a right drift and the other with a left drift. Which scene to use in block 2 and hence the first drift direction was assigned at random by the flow management programme which would also assign the other scene for block 3. Again this was done to counterbalance any participant bias related to initial drift.

3.5.7 Data measurement

The underlying C# scripts attached to the player object in the scenes controlled and enabled all activity as well as the collection and recording of data during the trials. In the Centre-line Following task, data included the Gabor horizontal position, drift direction and if static, the phase angle were collected every 20 frames (approximately every 330 ms) and in the Waypoint Collision task data included the Gabor position, block centre position, drift direction and if static, phase angle was collected when passing every block. This information was appended to the same file as the participant’s demographic records to ensure data integrity.

3.6 Procedure

The experiment comprised two experimental tasks. In the Centre-line Following task, the objective was to try and steered the patch onto and keep on the centreline as accurately as possible by moving the joystick. The Waypoint Collision task required participants to intercept the centre-line of on-coming rectangular blocks that were randomly positioned on the tube floor, by appropriately guiding the Gabor using the joystick.

Participants were run individually in single sessions where they completed both experimental tasks and which lasted approximately 35 minutes. Each participant completed both experiment tasks in a counterbalanced fashion such that the starting task alternated every next participant. The experimenter first familiarized each participant with the general nature of the experiment, the display, the task, how to proceed between screens and how to handle the joystick to steer the stimulus. Then each task commenced with a training block of 99 trials which was intended to be a practical familiarization for the participant with the environment, how to interact with it and its reaction demands. This training block could be exited anytime the participant felt confident enough to begin the main task.

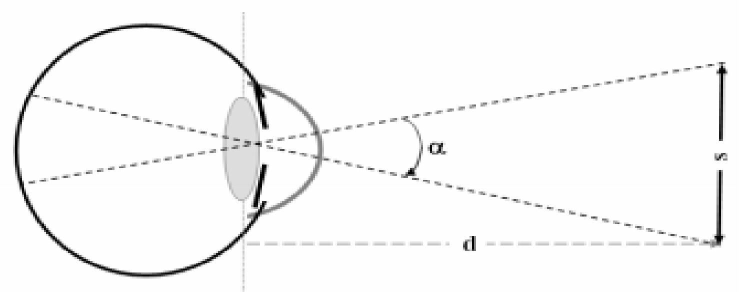
The first and last block of each task comprised a no-drift control condition. Also comparison of these blocks was used to measure any influence of fatigue or learning in general task execution when there is no local motion. These phases involved guiding the Gabor patch for 40 trials in each block. The patch was locally static in these blocks but phase shifted by one random value of the possible twenty angles between 0˚ and 342˚ in steps of 18˚. The phase angle was changed randomly every 20 trials. These two blocks took participants approximately 2 minutes each to complete.

In blocks 2 and 3, the main experimental phases, participants steered the patch through 80 trials each for a total of 160 trials. The patch drifted at a constant temporal frequency and its direction to the right or to the left was initially randomized, alternating direction every 20 trials. These two blocks took participants approximately 4 minutes each to complete. It was possible for the participant to take a short break between blocks and then proceed by clicking the ‘Next Block’ button.

3.7 Analysis

Participants’ performance in both tasks was measured as an error being the difference in position of the centre of the Gabor patch and the target location according to task. In the Centre-line following task the target location was the instantaneous position of the centre-line while in the Way-point Collision experiment the target was the centre-line of the rectangular block at the time of collision. Points towards the left of the pipe mid-line were taken as negative values while positive values relate points to the right of the mid-line. Therefore, in all the results, positive errors indicate when the Gabor was located to the right of the target while negative errors denote the patch being situated to the target's left, at the instant of measurement. The dependent measure for both tasks was the distance of the patch from the target here reported in terms degrees of arc of visual angle. Although absolute measurements in the experiment application are in Unity 'units' it is convenient to convert these to visual angle. This is implicitly done in the application code as already described in section 3.5.7.

It is convenient to measure distance in degrees of arc because it reflects perceived size that the measure subtends on the retina which is useful when comparing results from different studies as it already inherently accounts for the distance of the observer's eyes to the object under study. The equation below determines the visual angle ***α*** subtended at the eye lens by a



$$\alpha = 2 \times tan^{-1}\left(\frac{s}{2d}\right)$$

target size ***s*** viewed from a distance ***d***.

To ensure to screen for any results in which the participant was not performing coherently, trials where the perceptual error was more than three standard deviations away from the mean for each participant were reviewed for removal from the analysis.

Statistical analysis was done using IBM SPSS Statistics 24. To verify if the group mean errors within each drift condition differed systematically and significantly from the centreline on the floor of the pipe, the null hypothesis one-sampled t-tests were used. Factors and interactions of condition, pipe curvature direction, stimulus movement direction (for Way-point Collision only) and block were investigated for the dependent variable data across participants using repeated measures Analysis of Variance (ANOVA). Where indicated Greenhouse-Geisser correction was applied to adjust for violations of sphericity. The ANOVA models are detailed in the next section. The envelope global movement direction factor is considered because in the current study and especially in the Way-point collision task, the physical position of the patch is vigorously changed from left to right by participants' joystick actions, is additional to the local motion within the Gabor envelope. The global motion direction was measured immediately after each collision by recording the relative position, right or left, of the next target block from the current position.

4 Results

4.1 Data Screening

The raw data from both tasks was screened for consistency to ensure that there was no unsystematic participant activity especially since the tasks required a degree of familiarity in game interaction using the joystick. One participant was found to have 22% of data per main condition of drift more than three times the standard deviation away from the mean for the Centre-line Following task. Additionally for this task, a univariate boxplot analysis per participant of the z-scores of average errors across each interaction considered resulted in the same participant having outliers greater than 3 standard deviations for 41% of interaction factors. It seemed sufficiently clear that for some reason this participant had difficulty with the assigned task and it was decided to remove this subject's data from the analysis. Revised demographic data for the participant group whose experiment data was utilized is N = 13, $M_{\text{age}} = 27.2$, $SD_{\text{age}} = 7.25$, $Range_{\text{age}} = 20\text{-}47$. Of the participants 10 were female, 9 were right-handed and all had normal or corrected-to-normal vision.

4.2 Centre-line Following task

One-sample t-tests were performed to determine if the group mean errors within each drift condition varied consistently and significantly from the centreline on the floor of the pipe. During the ‘no drift’ blocks, on average, participants were able to guide the Gabor very closely to the centreline (M = .07, SE = .05). One sample t-test verified that the stimulus path and the centreline were not significantly different (t(12) = 1.47, n.s.).

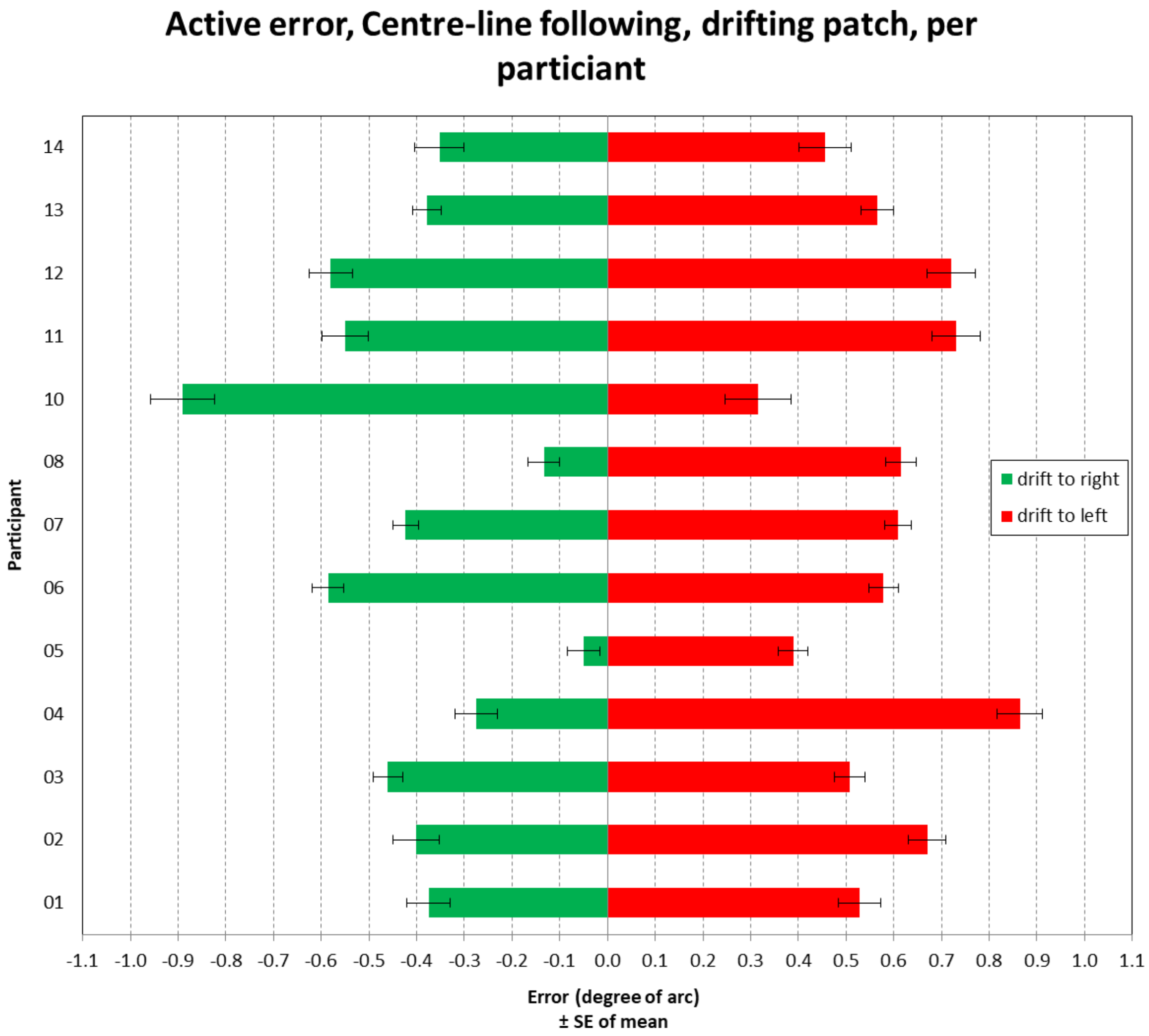


Figure 17. Centre-line following task, active error per participant

For conditions of patch drift there was a significant position bias consistently in the opposite direction to the drift. When the patch drift was to the left, participants counteracted by locating the Gabor to the right of the centreline (*M* = .57, *SE* = .04, *t*(12) = 14.14, *p* < .001) and when drift was to the right a reverse position shift of the stimulus was recorded (*M* = -.42, *SE* = .06, *t*(12) = -6.88, *p* < .001). Figure 17 shows that this effect was common to all participants when averaged over pipe bend direction and block. It is clear that for all subjects, local motion in one direction leads to consistent over-correction in the opposite direction as would be expected from a reaction to illusory MIPS.

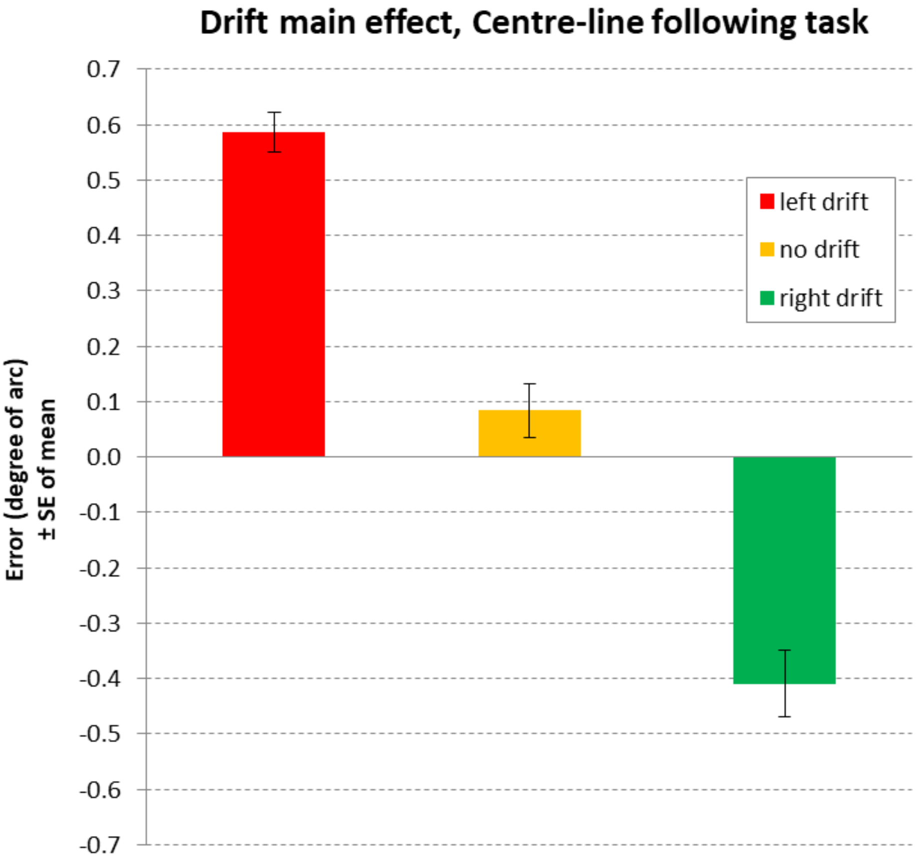


Figure 18. Centre-line following task, main effect of Gabor local drift

To explore the effect of pipe bends closely in front of stimulus and further along in the pipe, operationalized as the left or right direction of the bend to the end of the current pipe section and the direction of the bend of the next pipe section, a 3(drift – left, right or static) x 2(current pipe bend – left, right) x 2(next pipe bend – left, right) repeated measures ANOVA was conducted.

There was a significant main effect of drift, *F* (2, 24) = 157.47, *MSE* = .08, $p < .001$, $\eta^2 = 0.93$. Contrasts revealed that target deviation for left drift, *F* (1, 12) = 97.87, $p < .001$, $\eta^2 = 0.89$, and right drift, *F* (1, 12) = 113.42, $p < .001$, $\eta^2 = 0.90$, were significantly larger than in the static condition. As can be seen in Figure 18, the estimated marginal means indicate that here the effect of left drift was more pronounced than that of right drift.

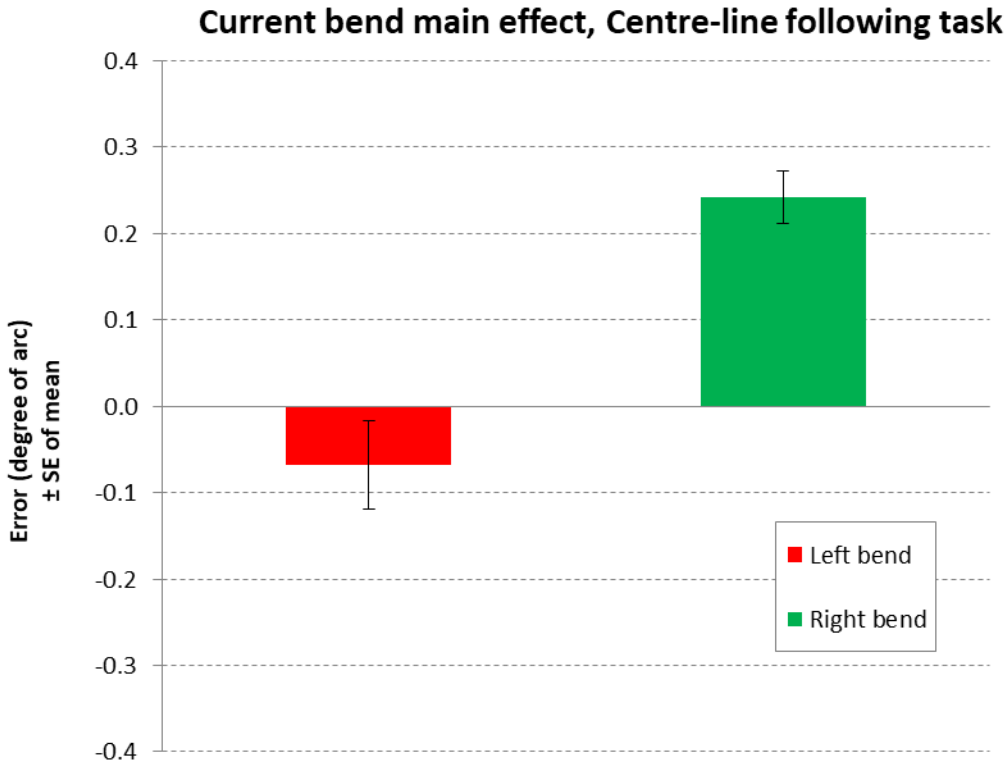


Figure 19. Centre-line following task, current bend main effect

The main effect of current pipe bend direction was also a significant effect on error, *F* (1, 12) = 58.28, *MSE* = .06, $p < .001$, $\eta^2 = 0.83$. This implies irrespective of the drift condition, the mean error on left bends was significantly different to that on a right bend direction. Figure 19 shows the estimated marginal means for this effect and indicates that participants had a tendency to oversteer into the bend with right bends having a larger influence on this error.

There was no main effect of next pipe bend direction, F (1, 12) = .04, MSE = .05, p = .84, η^2 = 0.04. Also no interaction effect was significant; drift x current pipe bend direction, F (2, 24) = .41, MSE = .05, p = .67, η^2 = 0.03; drift x next pipe bend direction, F (2, 24) = .7, MSE = .04, p = .51, η^2 = 0.06; current pipe bend direction x next pipe bend direction, F (1, 12) = .001, MSE = .01, p = .97, η^2 = 0.00; drift x current pipe bend direction x next pipe bend direction, F (2, 24) = .82, MSE = .03, p = .45, η^2 = 0.06.

To compare the effect of drift over repetitions, a 2(drift – left, right) x 2(block) repeated measures ANOVA was used. This compared blocks 2 and 3 of the experiment for both left and right drift across participants. Each block traversed 80 pipe sections. There was no main effect of block, F (1, 12) = .06, MSE = .12, p = .82, η^2 = 0.01. Also the interaction effect drift x block was not significant, F (1, 12) = 1.92, MSE = .09, p = .19, η^2 = 0.14. Since the Gabor position was continuously measured during the task, it was possible to plot the average error during a complete block of 2 epochs of left drift x 20 trials and 2 epochs of right drift x 20 trials. This visually shows the displacement of the stimulus from the centre-line as participants guided it over time. The markers indicate the position of the Gabor averaged over the sampling rate of measurements. The lines joining the markers represent the trajectory of the guided stimulus over time. Since the starting drift per epoch was counterbalanced two graphs are shown in Figure 20 representing the two possible combinations.

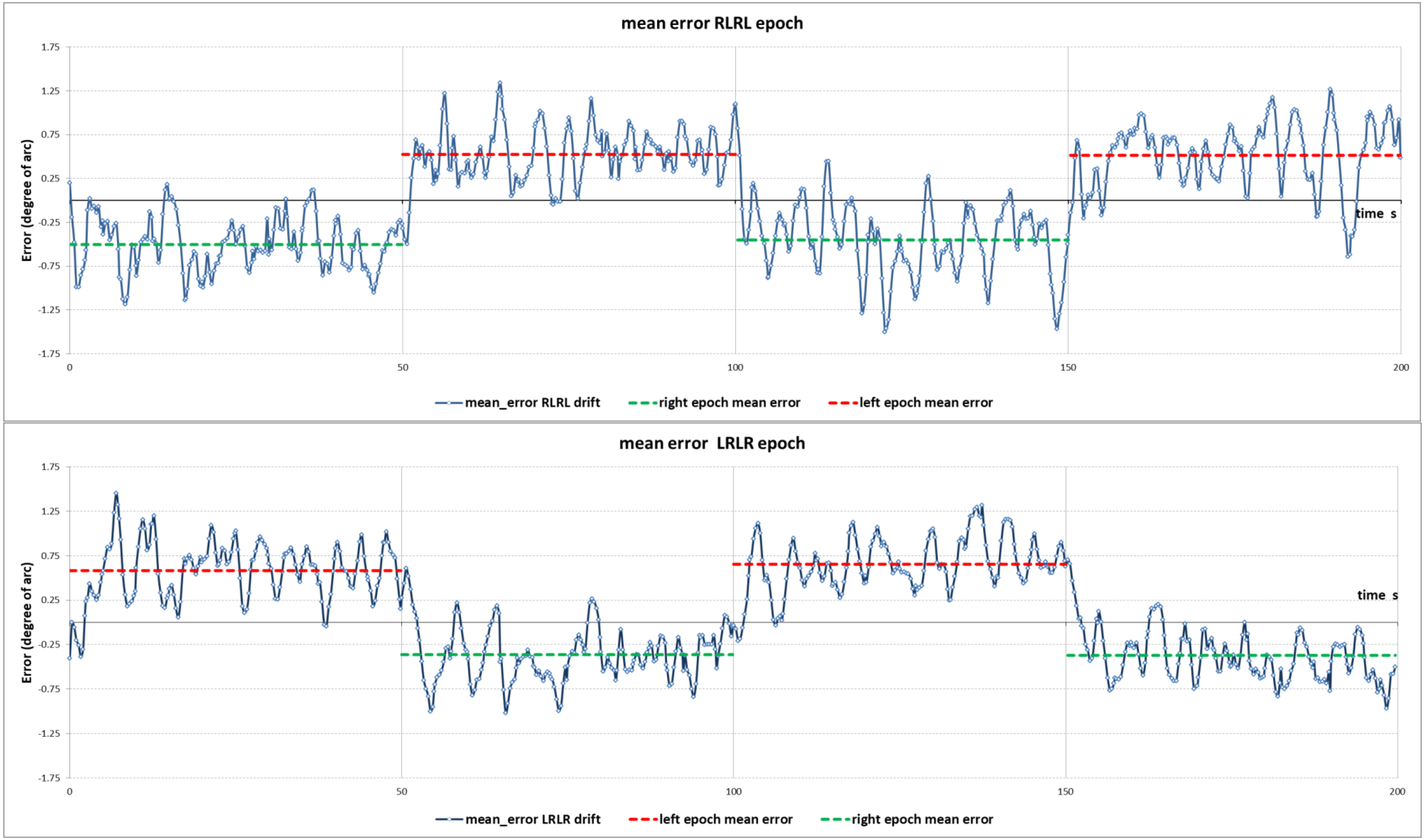


Figure 20. Centre-line following task, error from centre-line

A 2(current pipe bend – left, right) x 2(next pipe bend – left, right) x 2(block) repeated measures ANOVA was carried out to explore the effect of learning under the no drift condition. This compared blocks 1, the starting set of trials and block 4, the ending set of the experiment both of which had static local Gabor grating as a stimulus. There was no main effect of block, *F* (1, 12) = .17, *MSE* = .12, $p = .69$, $\eta^2 = 0.01$, however there was a significant current pipe bend x block interaction, *F* (1, 12) = 7.43, *MSE* = .07, $p = .018$, $\eta^2 = 0.38$. This interaction is depicted in

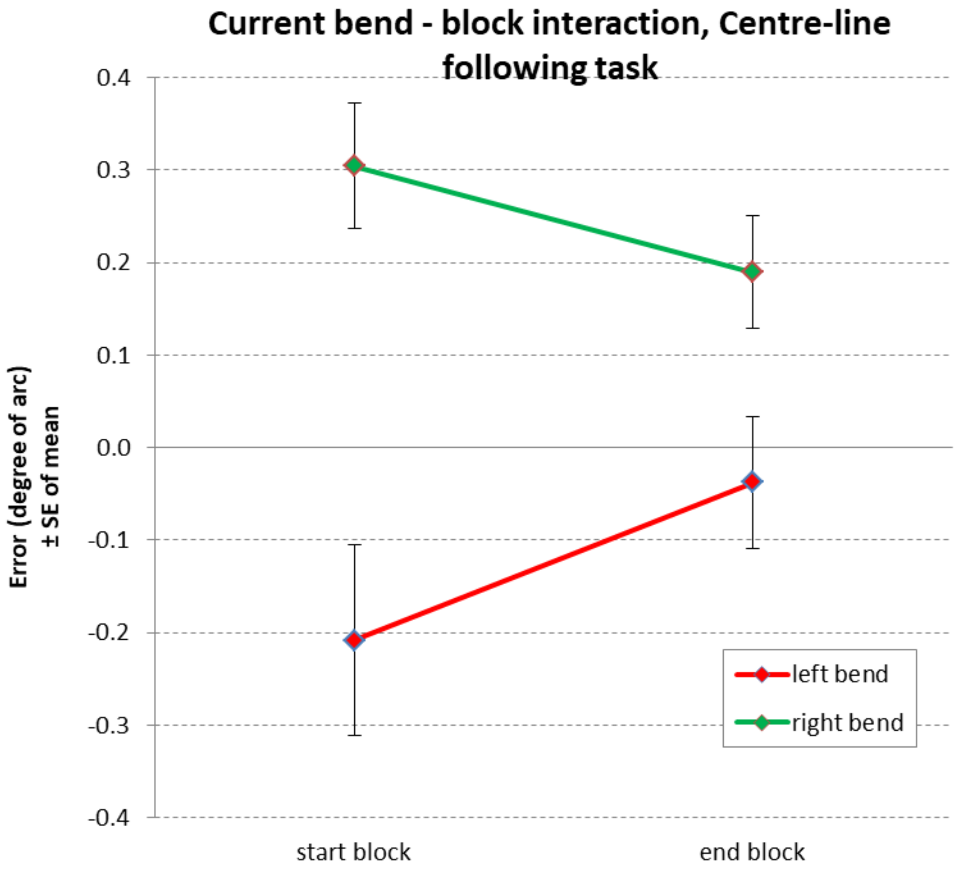


Figure 21. Centre-line following task, current bend – block interaction

Figure 21 which clearly shows a learning effect handling both left and right bends with reduced over-steering into the bend in ending blocks compared to starting blocks. The small tendency to over-steer into right bends more than into left bends can also be seen here.

4.3 Way-point Collision Task

Again for this task one-sample t-tests per condition were used to compare the mean deviation of participants' position of collision with the rectangular blocks from its centreline to no divergence from the centreline. For the 'no drift' condition, on average, participants were able to steer the Gabor to intercept blocks very near to their centreline (*M* = .02, *SE* = .10). A one sample t-test confirmed that these deviations were not significantly different to centring the block (*t*(12) = -.17, n.s.).

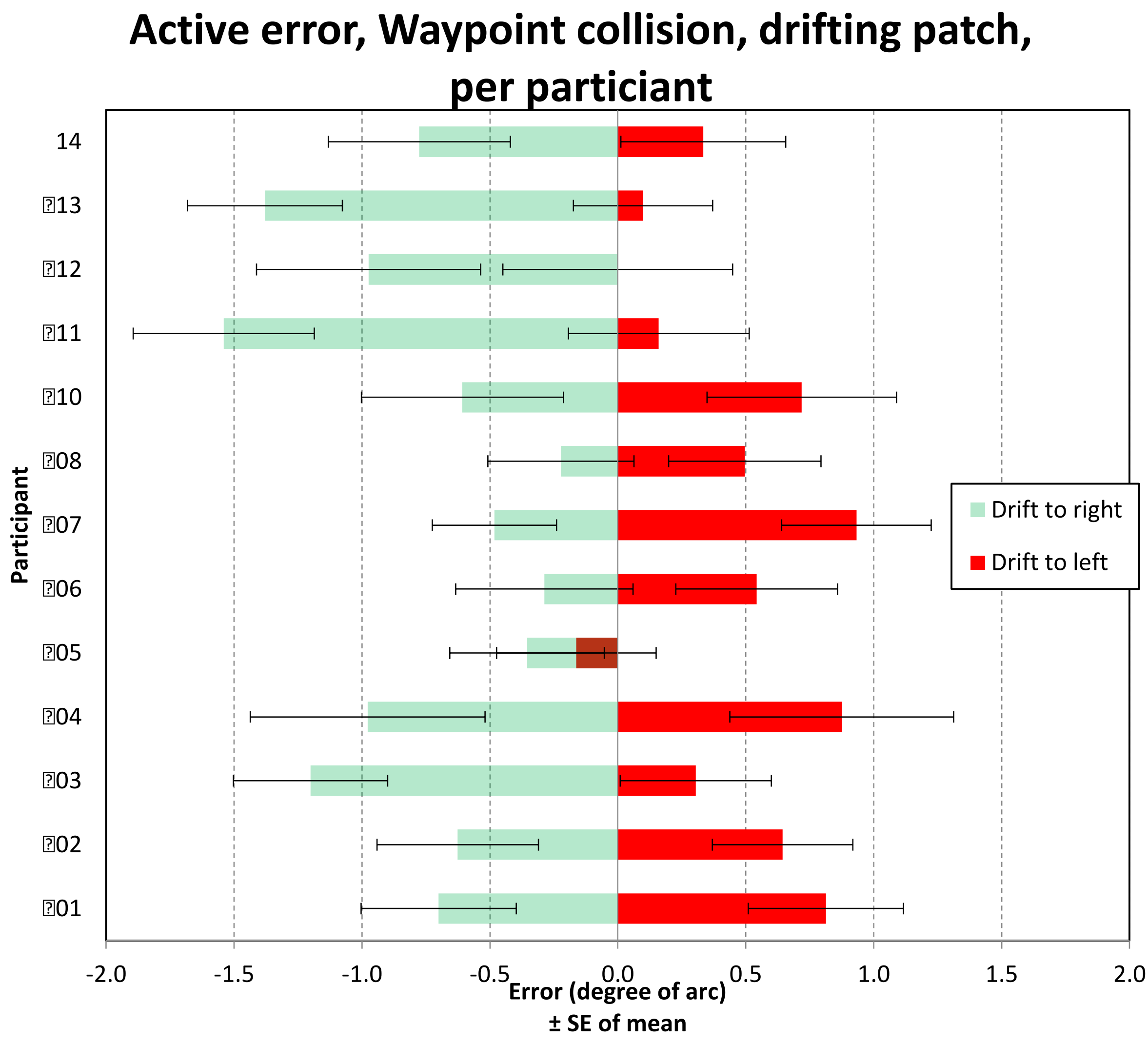


Figure 22. Waypoint collision task, active error per participant

When the patch drifted to the left participants compensated by tending to guide the Gabor to intercept the block significantly to the right of its centreline (M = .44, SE = .09, $t(12)$ = 4.54, p = .001). For conditions of right patch drift there was a significant collision position bias consistently in the opposite direction to the drift (M = -.78, SE = .12, $t(12)$ = -6.76, p < .001). All other factors being equal, this effect was common to all participants, except two, as shown in Figure 22. Participant 12, showed marginally left errors during left drift however means for left and right drift errors were still significantly different. However for participant 5 mean error difference between directions of drift was not significant, $M_{\text{left drift}}$ = -.16, $SE_{\text{left drift}}$ = .31, $M_{\text{right drift}}$ = -.35, $SE_{\text{right drift}}$ = .30, $t(79)$ = 1.99, p > .05.

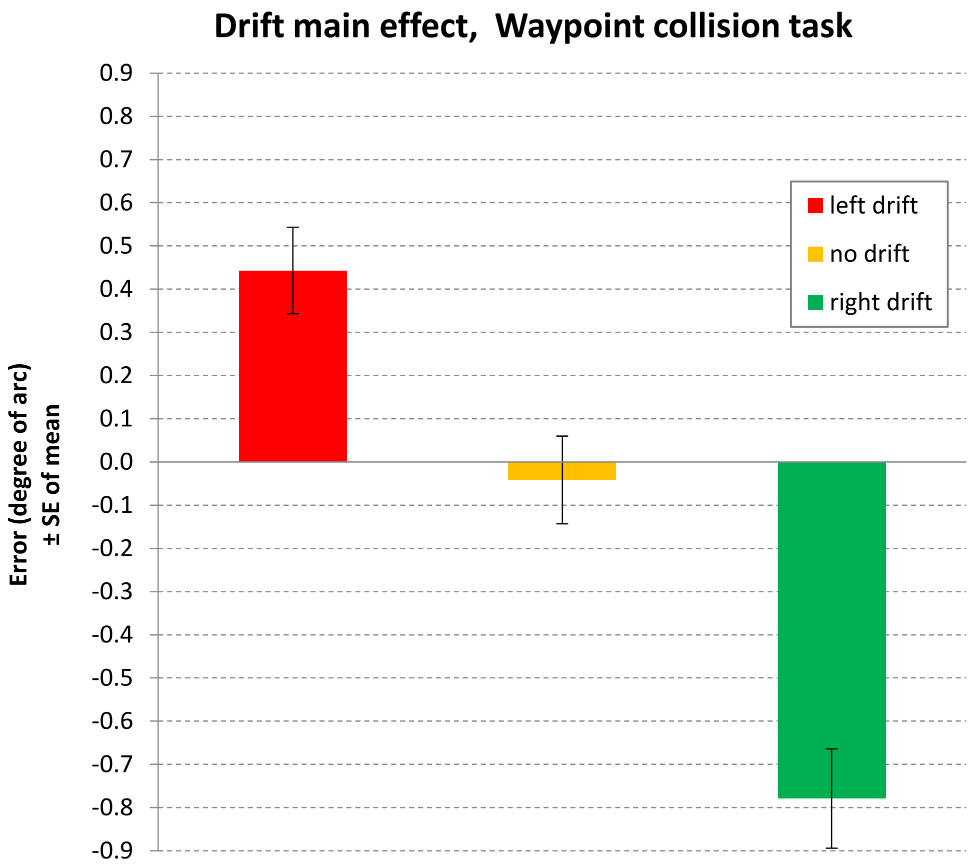


Figure 23. Waypoint collision task, drift main effect

In this task the interception target was located at the centre of every rectangular block positioned randomly on the pipe floor. Several future target blocks were visible to the participant and task performance therefore necessitated global left and right movement of the Gabor to successively hit the randomly positioned targets. In addition to exploring the effect of pipe bends as in the previous task, here the influence of stimulus global course of movement operationalised as the orthogonal left or right direction of the next rectangular block from the currently intercepted block was also considered. A 3(drift – left, right or static) x 2(current pipe bend – left, right) x 2(next pipe bend – left, right) x 2 (next block direction – left, right) repeated measures ANOVA was conducted.

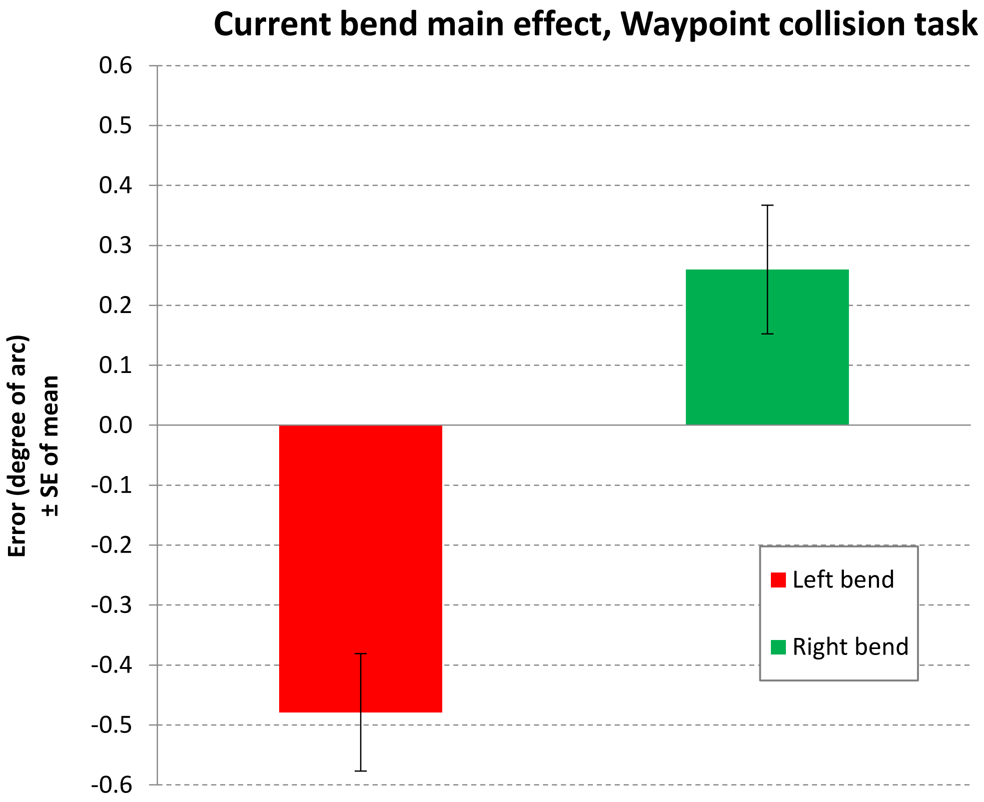


Figure 24. Waypoint collision task, current bend main effect

The main effect of drift was a significant, *F* (2, 24) = 77.03, *MSE* = .56, *p* < .001, η^2 = 0.87. Contrasts showed that target deviation for left drift, *F* (1, 12) = 55.32, *p* < .001, η^2 = 0.82, and right drift, *F* (1, 12) = 37.89, *p* < .001, η^2 = 0.76, were significantly larger compared to the static condition. As can be seen in Figure 23 the estimated marginal means indicate that here the effect of right drift was more marked than that of left drift.

There was a main effect of current pipe bend direction which had a significant effect on error, *F* (1, 12) = 26.91, *MSE* = 1.58, $p < .001$, $\eta^2 = 0.69$. This suggests that ignoring the drift condition and next bend direction, the mean error on current left bends was significantly different to that on a current right bend direction. Figure 24 shows the estimated marginal means for this effect implying that participants had a tendency to err in the direction of the next bend with left bends having a larger influence on this error. The main effect of next pipe bend

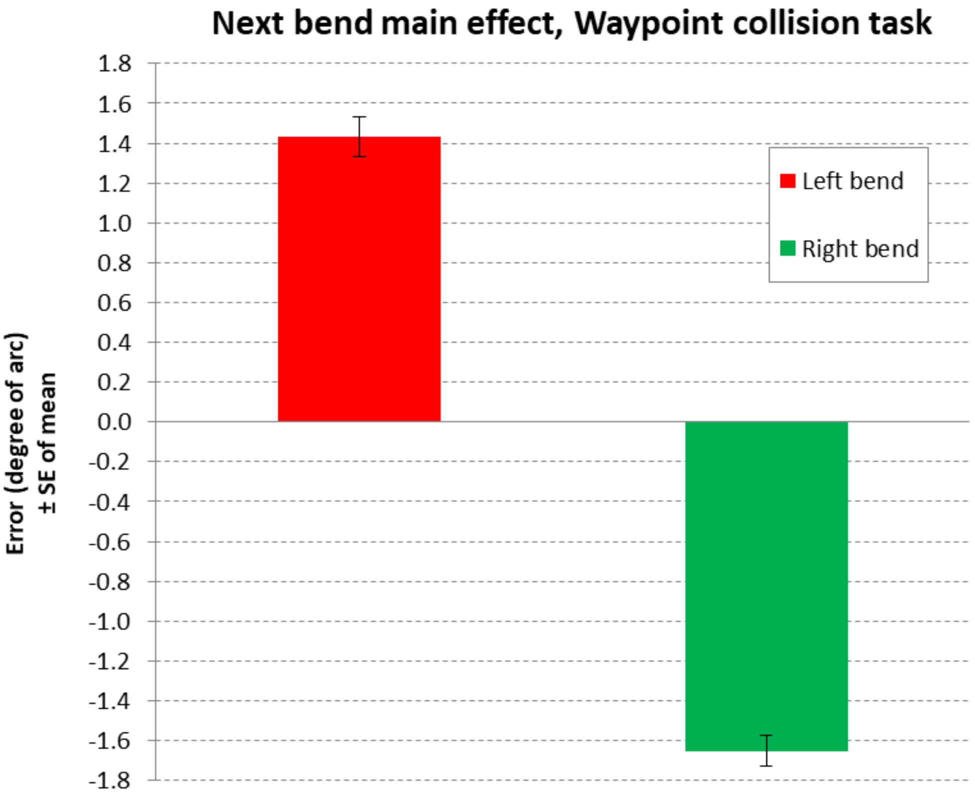


Figure 25. Waypoint collision task, next bend main effect

direction also had a significant influence on participants’ error, *F* (1, 12) = 1144.47, *MSE* = .65, $p < .001$, $\eta^2 = 0.99$, which indicates that aside of other factors the direction of the upcoming bend had a significantly different effect according to bend direction. The estimated marginal means for this effect are shown in Figure 25. Here it indicates participants would be influenced to intercept the target with an error in the opposite direction of the next bend.

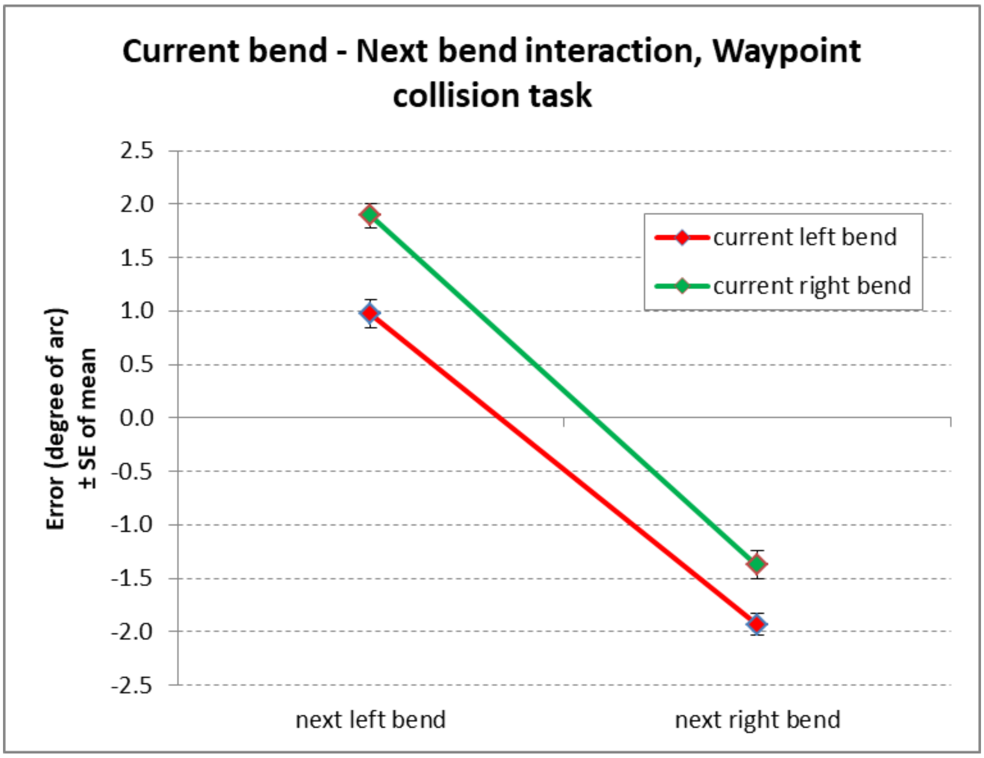


Figure 26. Waypoint collision task, next bend – current bend interaction

There is a marginally significant effect of current pipe bend direction x next pipe bend direction, *F* (1, 12) = 4.66, *MSE* = .55, *p* = .05, η^2 = 0.28. As shown in Figure 26 this effect indicates that the error direction of the effect of the next bend was modulated by the current bend direction. This influenced the error such that a next left bend caused a larger bias to the right if currently the stimulus is moving in a right bend and a next right bend would tend to bias a shift error more to the left if the current bend is to the left.

Considering only blocks 2 and 3 of the experiment for left and right drift with a 2(drift – left, right) x 2(block) repeated measures ANOVA did not yield any significant effects which suggests no effect of repetition. The effect of learning under the static local motion stimulus condition was explored using a 2(current pipe bend – left, right) x 2(next pipe bend – left, right) x 2 (next block direction – left, right) x 2(block) repeated measures ANOVA. This compared blocks 1, the starting set of trials and block 4, the ending set of the experiment both of which had static local Gabor grating as a stimulus. There were no significant effects of block, F (1, 12) = .17, MSE = .12, p = .69, η^2 = 0.01, or block interactions for this task.

Visually the participants' errors over the repeated right and left drift epochs of blocks 2 and 3 can be portrayed by showing a scatter plot of the interception errors from the rectangular block centre-lines over time. It should be noted that only the errors from the target centre-line are depicted here and the position of the target itself from the centre of the path is not represented. However each marker denotes the point in time of the interception of the Gabor with a rectangular block. Figure 27 depicts such plots of counterbalanced blocks with left and right drift starting epochs.

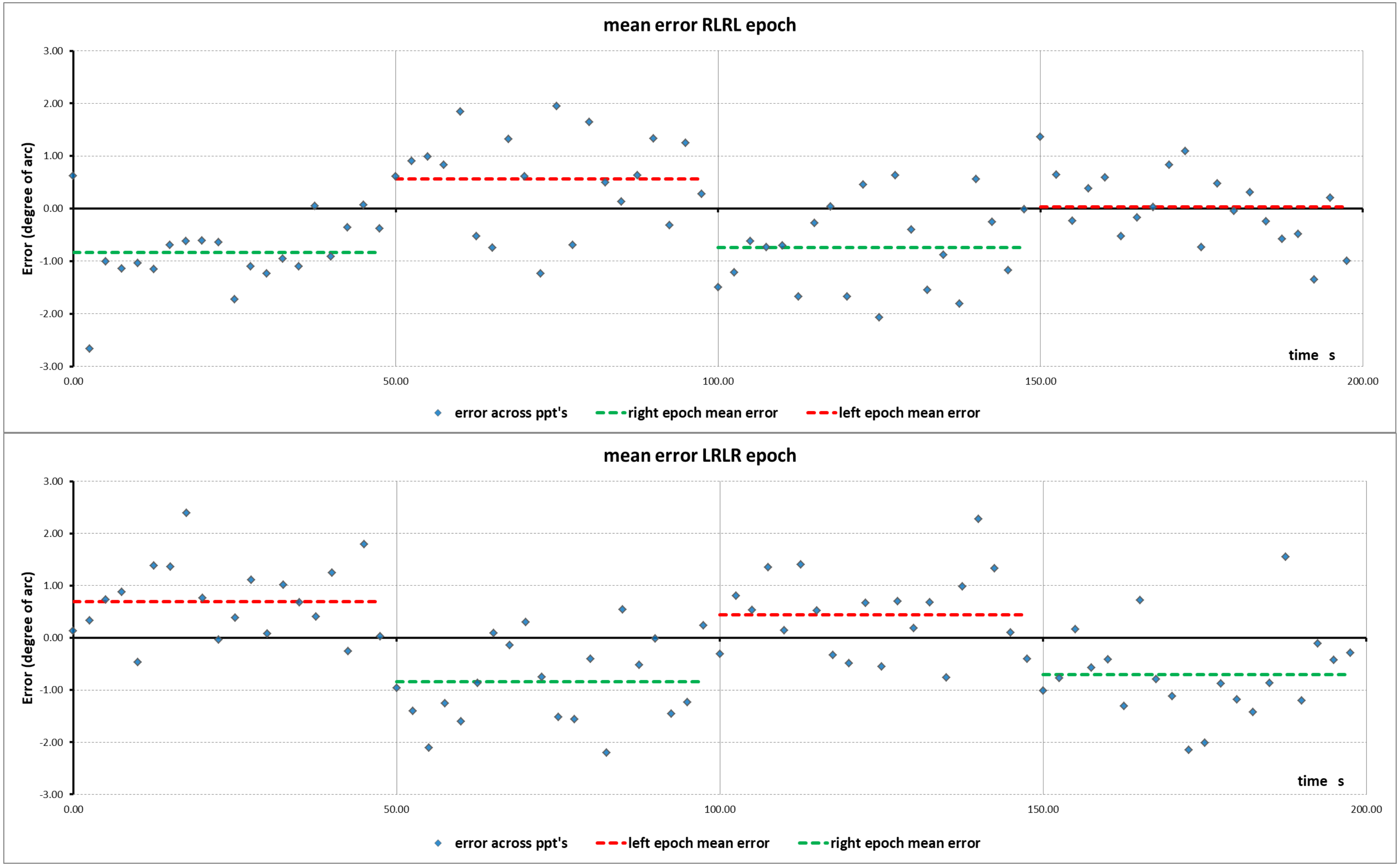


Figure 27. Waypoint collision task, error from blocks' centreline

5 Discussion

Two experiments were conducted to explore the effect of illusory position shift in a first person active, three dimensional scenario. The experimental setup took the form of a desktop 3D game environment where participants guided a locally stationary or drifting Gabor grating through a randomly curving tunnel to continuously intercept or follow designated targets. The impact of motion-induced illusory displacement on active control was measured by recording the deviation error of the stimulus from the target's centreline. In one task, participants were required to follow a curving line along the floor of the tunnel. Here the Gabor's variance of positon from this line was the measured error continuously recorded with the direction of local drift. The other task entailed participants steering the Gabor to collide with block objects lying along the floor of the tunnel. The error measured with local motion direction was the difference in positions of the Gabor and the blocks' centreline at the moment of impact.

5.1 General discussion

The general findings from this study were common to both experiments. Firstly, participants regularly compensated for the apparent position of the grating by adjusting the global position of the patch to the right when the local drift was to the left. Likewise, when the drift of the grating was to the right, the errors in position were to the left and with no drift participants could achieve the task without significant error. Many previous studies have reported motion-induced shifts in the position of a Gabor patch – the misperception of position in the direction of local motion of a stationary Gaussian window with an internal moving carrier (De Valois & De Valois, 1991; Ramachandran & Anstis, 1990; Chung, Patel, Bedell, & Yilmaz, 2007; Fu, 2004; Hisakata & Murakami, 2009; Bressler & Whitney, 2006). The current study is consistent with these findings, and it is suggested that in trying to keep the stimulus perceptually centred participants misguided its position by unwittingly adjusting it in the opposite direction of the local drift and illusory displacement. This is also in-line with findings in most other studies conducted on interaction with drifting Gabors in global movement (de la Malla, Smeets, & Brenner, 2018; Caniard, Bülthoff, Mamassian, Lee, & Thornton, 2011; de la Malla, Brenner, de Haan, & Smeets, 2019; Yamagishi, Anderson, & Ashida, 2001) although Marinovic, Plooy, & Arnold (2012) found no errors in a directly interceptive task compared to a perceptual task. In all these studies the stimuli were presented in 2 dimensional flat spaces. The current study suggests that the influence of the illusory position shift due to motion extends to action performed in a 3D setting.

The second general finding is that the global position of the patch is continuously influenced by the local drift and there does not seem to be an adaptation over time. In both experiments, charting of the right drift – left drift epochs clearly shows that the mean error is sustained throughout the length (200s per epoch) of these phases of the experiments. This agrees with the findings of Caniard et al., (2011) and extends these to a 3D environment. It is to be noted however that in the centre-line following task there was a recorded significant reduction in position error arising from the direction of the current bend, between the starting block and ending block in the no-drift condition. This is interpreted as an effect of learning and will be discussed further below.

The third general outcome, which is implicit in the other findings, is that first person active control did not remove the performance errors arising in drift conditions as compared to the negligible mean errors for a locally static stimulus. Indeed participants implemented a trajectory that consistently shifted the stimulus in the opposite direction to that of the local drift. This agrees with the findings of Caniard et al., (2011) and Caniard, Bülthoff, & Thornton, (2015). Since both the experiments involved the participant in explicit visuomotor control, here comparison can only be made between left/right drift conditions with the active control in the non-drift condition. Devising an alternative 3D game where the participant can be a passive judge of perceptual errors would establish an effect baseline for comparison with the active tasks and with other studies. This is a good candidate for future studies.

Comparing the magnitudes of the errors between experiments shows that left drift effects resulted in similar position shifts. Paired t-tests indicate that there is no significant difference between left drift error means for the two tasks ($M_{\text{waypoint collision}} = .44^{\circ}$, $SE_{\text{waypoint collision}} = .09$; $M_{\text{centreline following}} = .57^{\circ}$, $SE_{\text{centreline following}} = .04$; $t(12) = -1.3$, $p > .05$) and the absolute magnitude is, albeit on the high side, comparable to position shift effects ($.03^{\circ}$ to $.4^{\circ}$) recorded in other studies using various methodologies (De Valois & De Valois, 1991; Kerzel & Gegenfurtner, 2005; Chung et al., 2007; Arnold, Thompson, & Johnston, 2007) . For right drifts however the paired t-tests indicated significantly different mean errors ($M_{\text{waypoint collision}} = -.78^{\circ}$, $SE_{\text{waypoint collision}} = .12$; $M_{\text{centreline following}} = -.42^{\circ}$, $SE_{\text{centreline following}} = .06$; $t(12) = -3.17$, $p < .05$). Also in absolute terms the waypoint collision task error mean is higher than as found in other studies even by Caniard et al., 2015 who acknowledged high shift error results in their experiment. This discrepancy can possibly be explained by looking at the standard error in the waypoint collision task which is large compared to the centreline following task, indicating that the mean for right drift error in the former is very noisy and should be considered with caution. This noise is also evident in Figure 22 as relatively high standard error of participants' individual performance at this task. While both tasks required tracking the curvatures of the tunnel, a major difference is that in the waypoint collision task it was also necessary to intercept looming targets. It is possible that in part, the increase in noise in this task is an artefact of the additional demands of interception. For example, it has been frequently reported in studies that the subjective percept of distance from an observer to an object is deemed to be shorter in virtual than in natural environments (Renner et al., 2014). In another experiment designed to simulate a natural ball-catching task, it was found that participants could not accurately judge the approach speed and potentially time-to-contact (Rushton & Duke, 2009). These could be typical factors in the waypoint collision task 3D simulated environment that drive the noisy results and is discussed further in the next section.

Future studies could review and possibly neutralise such influences through appropriate development enhancements of the virtual reality game experiment.

Allied with the above observations is another effect reported in the results of the two experiments. In the centreline following task, the curvature direction of the tunnel at the position of the stimulus has an influence on the centreline deviation error, indicating participants had a tendency to oversteer into the bend. So a left bend would veer to a left error and a right bend to a right error, ($M_{\text{right bend}} = .24$, $SE_{\text{right bend}} = .03$; $M_{\text{left bend}} = -.07$, $SE_{\text{left bend}} = .05$), but the upcoming bend direction did not significantly influence the position error. Similarly in the way point collision task the current bend direction had an analogous although stronger effect, ($M_{\text{right bend}} = .26$, $SE_{\text{right bend}} = .11$; $M_{\text{left bend}} = -.48$, $SE_{\text{left bend}} = .10$). However, here the next bend direction and its interaction with current curve direction were a strong significant influence to understeer and potentially overshoot a target, ($M_{\text{right bend}} = -1.65$, $SE_{\text{right bend}} = .08$; $M_{\text{left bend}} = 1.43$, $SE_{\text{left bend}} = .10$). The importance of the position of looming blocks in an interception task has already been highlighted above and the direction of the next bend is relevant in estimating the point of contact. The relevance of the next bend in the waypoint collision task could indicate that here participants were often moving their gaze from the bottom of the screen where the stimulus was situated, to the centre of the screen to assess upcoming curves. This would imply that the Gabor was intermittently being viewed peripherally rather than centrally. Previous studies have shown that eccentricity enhances illusory position shift, increasing it by 1 to 2 arc mins per degree (Chung et al., 2007; De Valois & De Valois, 1991). With the monitor used in the current experiment, the peripheral visual angle between the centre and bottom of the display would be approximately 13˚ so resulting in a greater illusory effect than when the gaze was central. This intermittent eccentricity possibly contributed to the noisy errors reported for this task. Furthermore, if gaze was shifted to the left or right directions along current or future bends or towards looming obstacles this might have corresponded to a steering swing in that direction

(Readinger, Chatziastros, Cunningham, Bülthoff, & Cutting, 2002). There is a likelihood that the direction of gaze or allocation of attention differed between the two tasks. It would therefore be instructive to extend this study in future by adding eye-tracking data to allow an insight into gaze direction and saccadic movements.

A third difference in the results of the two experiments is that while in the waypoint collision task there were no significant effects between experiment blocks, in the centre-line following task there was a significant interaction between direction of bend being followed and the start block and end block in the no-drift condition. This manifested in a reduction in position error when tackling both right and left bends. As in these block there was no local motion of the Gabor, the error in question is probably a resulting artefact of the game design and interface rather than due to an illusory percept. It is known that rehearsing an action results in improved perceptual discernment of the same action (Veto et al., 2018) and here it seems that the actions taken to handle the joystick and negotiate a bend improved with practice. In the current study acquaintance with the game was not a rigid process and left up to each participant. For future studies, this possibly points at the importance of formalising the training of participants to better familiarize them with the game before collecting experimental data.

In these experiments there are various motions at work which combine in the manifestation of the positional errors observed. The stimulus configuration has at least three co-varying factors in spatiotopic coordinates: the local carrier velocity and the envelope velocity which has two components – a horizontal velocity which is varied by the participant operating the joystick and a fixed orthogonal velocity in depth towards the horizon. Previous studies have found that when a Gabor envelope viewed peripherally moves in a direction orthogonal to its internal grating drift, the apparent direction of its trajectory can have a deviation of 45˚ or more from the actual path (Tse & Hsieh, 2006; Kwon, Tadin, & Knill, 2015; Lisi & Cavanagh, 2015). Because the depth velocity has been fixed in these tasks, it is not possible to unpick an effect due to it. A future experimental design could feature envelope velocity as an independent factor which would be of particular interest since velocity ‘into’ the display is a distinguishing characteristic of the 3D environment being simulated.

5.2 Methodological factors

From the above it would seem that although there is clear evidence of a systematic effect of embedded motion on global positional error in both experiments, however the magnitudes and variances of these errors also indicate other possible methodological causes.

One of the goals of this study was to enact an action-perception experiment in a simulated environment generated using 3D game development software. An important facet in developing the game was the concept of a curving pipe through which the participant would steer a stimulus as a first person driver. The physics of this movement needed to realistically model the forward trajectory of the Gabor and first person such that if no sideways action is initiated by the participant via the joystick, the patch would follow a tangential path forward toward the tunnel wall. Indeed besides MIPS, the significant effects on positional error were found to be related to current and next bend curvature directions. It is pertinent therefore to consider some reported effects on perception of spacial motion in virtual environments.

How space is perceived in VR can cause difficulties. For example, first person motion is typically different from that in the real world because of a number of inherent factors like latency and inferior time-based resolution. Also, motion perception in virtual environments is based on integration of weighted inputs that provide motion cues. In this study for example, the percept of motion was generated from the results of calculations of the geometry of forward movement in a curving tunnel convoluted with a horizontal movement (of the stimulus) in the frontoparallel plane. It has been shown that such facets of virtual environments can significantly influence observers’ perception of dimensions and self-motion. This is often observed in mis-estimating distances or rotations in visual self-motion perception. (Bruder, Steinicke, Wieland, & Lappe, 2012). For example, it has been frequently reported in studies that the subjective percept of distance from an observer to an object is deemed to be shorter in virtual than in natural environments (Renner et al., 2014).

In many studies this has been manifest as a comparative difference between judging distance and perceptual actions. The mis-estimation of size and distance in virtual environments has been found both with monocular and binocular vision, with different fields of view and also if an observer is given motion parallax and stereoscopic depth cues (Wilson & Soranzo, 2015). This effect has been explained by Bingham, Bradley, Bailey, & Vinner (2001) in the context that what we see as an object in a virtual environment is a display which mediates a sequence of images that represent an object. Because an observer’s eyes are focused on the display’s focal plane while the object is perceived at a deeper location there is conflict between accommodation (the extent of curvature in eye lenses due to the fixed viewing distance between the user and the display) and vergence (the extent of convergence of the eyes to the objects virtual depth of focus). This conflict of two mechanisms that are intimately linked in the real world could be the cause of underestimation of depth in virtual space. Some studies have suggested the necessity of perception-action systems recalibration and rescaling of the perceived space in virtual environments (Wilson & Soranzo, 2015).

While both tasks in the current study required tracking the curvatures of the tunnel, a major difference is that in the waypoint collision task it was also necessary to intercept looming targets. It is possible that in part, the increase in noise measured for this task is an artefact of the additional demands of interception. In an experiment designed to simulate a natural ball-catching task, Rushton & Duke (2009) found that participants could not accurately judge the approach speed and potentially time-to-contact at interception which highlights the difficulty of targeted collisions in a specified location. Experiments carried out by Bertin, Israël, & Lappe (2000) where they used optic flow stimuli to simulate curvilinear 2D trajectories over a horizontal ground plane in a virtual environment, indicate a further issue that could potentially have made interception more problematic in the waypoint collision task. They showed that in a virtual environment where no physical movement of the observer’s head takes place and hence using only visual cues to perceive self-motion, participants tended to underestimate the curvature of a semicircle in a facing forward condition and overshoot the target end point. This is similar to the next bend main effect observed in the waypoint collision task and could possibly indicate that such an effect might be an artefact of the virtual environment.

As the above suggests utilizing VR to create perceptually-faithful simulations can have some issues which need to be overcome by further refinements in the model coding not only to replicate real-world physics but also to account and possibly calibrate for the findings that in virtual settings can have on motion and perception itself.

5.3 Limitations

Although the results of the current study are similar to the general outcomes from previous research, without a specific perceptual task as a control condition it was not possible to compare the results of active control to a passive scenario. This is a limiting factor since we cannot resolve whether in a 3D environment, active control leads to greater or lesser errors of position determination.

Another limitation is that we cannot determine if and when the stimulus was being viewed peripherally or centrally. Since eccentricity can impact the illusory position shift, eye tracking would have allowed for distinguishing this factor and estimate its effect.

More formalised and controlled assessments of participants’ familiarity with the ‘games’ used in the experiments could have resulted in less noisy results especially in the more demanding waypoint collision task. Having participants assess their own fluency with the applications turned out to be a minor limitation.

An allied limitation is that the experiment analysed and found consistent Gabor drift-mis-location results within participants but has not tested variation between individuals.

Indeed the graphical results especially in the waypoint collision task indicated such disparity between participants which is consistent with other findings in visuomotor research (Parker et al., 2017; de la Malla et al., 2018). Not considering individual differences could have contributed to higher average signal to noise ratios or masked participant factors that could have influence the results. Future studies might allow for and explore between subjects factors.

A number of limitations highlighted in the discussion above also expectedly arose from the current software development stage of the game and virtual environment itself.

5.4 Practical Implications

Notwithstanding the limitations, the study found evidence that the apparent position shift in the direction of local motion is also effective in a 3-dimensional environment even when perceptual action is involved. At the very least the study established that in a displayed virtual environment precise visuomotor interactions in the presence of local motion could be erroneous. In practical terms the display could be in say a vehicle where an on-board computer generates a 3-dimensional simulated view on a touchscreen display or head-up display. Steering the vehicle based on active interaction with the display could depend on hand movements. This study is suggesting that these actions might be affected by perceptual illusions such as MIPS which if inaccurate and depending on the task could have serious consequences.

Designing out such perceptual errors could explore using other means of interacting with displays that would be immune or less effected by visual illusions. Another method would be to model the illusory perception effect on interception and be able to predict its extent also accounting for individual differences and display types. The modelled prediction could be used to adjust the generated display in a way that eliminates or improves users' performance. Indeed the ideal simulated displayed reality in these cases might not be one that impeccably imitates the real world but rather one that interprets the characteristics of visual perception and generates a view of the world that accounts for these accordingly.

5.5 Future studies

The study results and limitations give direction to a number of possibilities for future development and research.

Generally it is suggested that eye-tracking data collection should be facilitated in all future developments of this experiment. This not only provides awareness of gaze locations to determine stimulus eccentricity and objects attended but also delivers saccade information which analysed can be a basis for comparison with other studies. Eye-tracking capabilities would also allow for extending the study in line with other research (de la Malla et al., 2018; De La Malla et al., 2017; van Heusden et al., 2018) that uses saccade data to build models that predict action-perception effects.

One potential project is developing a version of the current 3D game-experiment where the participant can be a passive judge of positional errors, viewing a system-driven stimulus intercepting a target with system determined positional offsets. The point-of-view of the 3D simulation would be a first-person passive one to mirror the current active study. Psychophysics methodologies could then be used to describe the performance level. This perceptual task would establish an effect baseline for comparison with the active tasks of this study and with other research (Caniard et al., 2011; Caniard et al., 2015).

Another line of investigation in the 3-dimensional setting would be to explore individual differences in performance not necessarily due only to ‘training’. Allied to this, studies could be directed at building a predictive computational model perhaps calibrated per participant of say the predicted error in an active interception task calculated as a function of the perceptual error due to MIPS in passive mode and the perceptual error in judging speed due to the virtual environment setting. Guided by work in other studies (for example, de la

Malla et al., 2018; Aguilar-Lleyda et al., 2018) this could be fruitful in further understanding MIPS in the 3-dimensional context but also in directing practical applications.

This current project created the basis for a 3D experimental environment using game development software. A future project could firstly capitalise on the experience gained both in development platform familiarity and also in the game's experimental usage by revising code critical to improving application performance and precision as outlined in the discussion above. However, it would also be possible to enhance the code to deliver full Virtual Reality for a HMD. This would allow for a fuller immersive experience, a realistic 3D environment and the possibility to tightly control aspects of the stimulus and to interact with virtual objects using virtual limbs in peripersonal and extrapersonal virtual space. This somewhat generalizes the application as a research tool and opens it to wider experimental possibilities.

5.6 Conclusion

This study had the goal to explore the influence of motion-induced position shifts during active perceptual tasks in a 3D environment. A novel game experiment was created using Unity3D to measure and analyse the effect of action under globally moving but locally static or drifting visual stimuli. In one task, participants were required to follow with a drifting Gabor patch a curving line along the floor of a virtual tunnel. The other task entailed participants steering the Gabor to collide with block objects lying along the floor of the tunnel. Clear evidence suggesting an effect of embedded motion on global positional error was recorded in both tasks. The current study suggests that the influence of the illusory position shift due to motion extends to action performed in a 3D setting. From a practical standpoint, these results established that in a displayed virtual environment precise visuomotor interactions in the presence of local motion could be erroneous which provides a clear indicator in the design of display ergonomics.

The underlying game design and framework of the experiment contributed to experience that would enable enhanced developments of this tool application for future visual perception studies. Several such further studies have been suggested.

References

Adelson, E. H., & Bergen, J. R. (1985). Spatiotemporal energy models for the perception of motion. *Journal of the Optical Society of America. A, Optics and Image Science*, *2*(2), 284–299. https://doi.org/10.1364/JOSAA.2.000284

Aguilar-Lleyda, D., Tubau, E., & López-Moliner, J. (2018). An object-tracking model that combines position and speed explains spatial and temporal responses in a timing task. *Journal of Vision*, *18*(12), 12. https://doi.org/10.1167/18.12.12

Arnold, D. H., Thompson, M., & Johnston, A. (2007). Motion and position coding. *Vision Research*, *47*(18), 2403–2410. https://doi.org/10.1016/j.visres.2007.04.025

Bertin, R. J. V., Israël, I., & Lappe, M. (2000). Perception of two-dimensional, simulated ego-motion trajectories from optic flow. *Vision Research*, *40*(21), 2951–2971. https://doi.org/10.1016/S0042-6989(00)00134-6

Bingham, G. P., Bradley, A., Bailey, M., & Vinner, R. (2001). Accommodation, occlusion, and disparity matching are used to guide reaching: A comparison of actual versus virtual environments. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(6), 1314–1334. https://doi.org/10.1037/0096-1523.27.6.1314

Braddick, O. J., & Curran, W. (2002). Directional performance in motion transparency. *Vision Research*, *42*(10), 1237–1248. https://doi.org/10.1016/S0042-6989(02)00018-4

Bradley, D. C., & Goyal, M. S. (2008, September 13). Velocity computation in the primate visual system. *Nature Reviews Neuroscience*. https://doi.org/10.1038/nrn2472

Bressler, D. W., & Whitney, D. (2006). Second-order motion shifts perceived position. *Vision Research*, *46*(6–7), 1120–1128. https://doi.org/10.1016/j.visres.2005.10.012

Bridgeman, B., Hendry, D., & Stark, L. (1975). Failure to detect displacement of the visual world during saccadic eye movements. *Vision Research*, *15*(6), 719–722. https://doi.org/10.1016/0042-6989(75)90290-4

Bruder, G., Steinicke, F., Wieland, P., & Lappe, M. (2012). Tuning self-motion perception in virtual reality with visual illusions. *IEEE Transactions on Visualization and Computer Graphics*, *18*(7), 1068–1078. https://doi.org/10.1109/TVCG.2011.274

Brysbaert, M. (2019). How many participants do we have to include in properly powered experiments? A tutorial of power analysis with some simple guidelines. *PsyArXiv*. https://doi.org/10.31234/OSF.IO/2V4YX

Brysbaert, M., & Stevens, M. (2018). Power Analysis and Effect Size in Mixed Effects Models: A Tutorial. *Journal of Cognition*, *1*(1). https://doi.org/10.5334/joc.10

Burlingham, C., & Heeger, D. (2018). Heading Perception Depends on Time-Varying Evolution of Optic Flow. *Journal of Vision*, *18*(10), 47. https://doi.org/10.1167/18.10.47

Burr, D., & Thompson, P. (2011). Motion psychophysics: 1985-2010. *Vision Research*, *51*(13), 1431–1456. https://doi.org/10.1016/j.visres.2011.02.008

Caniard, F., Bülthoff, H. H., Mamassian, P., Lee, S.-W., & Thornton, I. M. (2011). Active control does not eliminate motion-induced illusory displacement. *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception in Graphics and Visualization*, *1*(212), 101–108. https://doi.org/10.1145/2077451.2077470

Caniard, F., Bülthoff, H. H., & Thornton, I. M. (2015). Action can amplify motion-induced illusory displacement. *Frontiers in Human Neuroscience*, *8*(January), 1–14. https://doi.org/10.3389/fnhum.2014.01058

Cavanagh, P., & Anstis, S. (2013). The flash grab effect. *Vision Research*, *91*, 8–20. https://doi.org/10.1016/j.visres.2013.07.007

Chung, S. T. L., Patel, S. S., Bedell, H. E., & Yilmaz, O. (2007). Spatial and temporal properties of the illusory motion-induced position shift for drifting stimuli. *Vision Research*, *47*(2), 231–243. https://doi.org/10.1016/j.visres.2006.10.008

Clark, D. A., & Demb, J. B. (2016, October). Parallel Computations in Insect and Mammalian Visual Motion Processing. *Current Biology*. https://doi.org/10.1016/j.cub.2016.08.003

Creem-Regehr, S. H., & Kunz, B. R. (2010). Perception and action. *Wiley Interdisciplinary Reviews: Cognitive Science*, *1*(6), 800–810. https://doi.org/10.1002/wcs.82

Cropper, S. J. (2001). Local and Global Motion Signals and their Interaction in Space and Time. In J. Zanker, Johannes M. Zeil (Ed.), *Motion Vision - Computational, Neural, and Ecological Constraints* (1st ed., pp. 113–124). Springer Verlag.

de la Malla, C., Brenner, E., de Haan, E. H. F., & Smeets, J. B. J. (2019). A visual illusion that influences perception and action through the dorsal pathway. *Communications Biology*, *2*(1), 38. https://doi.org/10.1038/s42003-019-0293-x

de la Malla, C., Smeets, J. B. J., & Brenner, E. (2018). Errors in interception can be predicted from errors in perception. *Cortex*, *98*, 49–59. https://doi.org/10.1016/j.cortex.2017.03.006

De La Malla, C., Smeets, J. B. J., & Brenner, E. (2017). Potential Systematic Interception Errors are Avoided When Tracking the Target with One's Eyes. *Scientific Reports*, *7*(1), 10793. https://doi.org/10.1038/s41598-017-11200-5

De Valois, R. L., & De Valois, K. K. (1991). Vernier acuity with stationary moving Gabors. *Vision Research*, *31*(9), 1619–1626. https://doi.org/10.1016/0042-6989(91)90138-U

Del Grosso, N. A., & Sirota, A. (2019). Ratcave: A 3D graphics python package for cognitive psychology experiments. *Behavior Research Methods*. https://doi.org/10.3758/s13428-019-01245-x

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, *41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Franz, V. H., & Gegenfurtner, K. R. (2008). *Grasping visual illusions: Consistent data and no dissociation*. *Cognitive Neuropsychology* (Vol. 25). https://doi.org/10.1080/02643290701862449

Fredericksen, R. E., Bex, P. J., & Verstraten, F. A. J. (1997). How big is a Gabor patch, and why should we care? *Journal of the Optical Society of America A*, *14*(1). https://doi.org/10.1364/josaa.15.001959

Freyd, J. J., & Finke, R. A. (1984). Representational momentum. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *10*(1), 126–132. https://doi.org/10.1037/0278-7393.10.1.126

Fu, Y.-X. (2004). Asymmetry in Visual Cortical Circuits Underlying Motion-Induced Perceptual Mislocalization. *Journal of Neuroscience*, *24*(9), 2165–2171. https://doi.org/10.1523/jneurosci.5145-03.2004

Furlan, M., & Smith, A. T. (2016). Global Motion Processing in Human Visual Cortical Areas V2 and V3. *Journal of Neuroscience*, *36*(27), 7314–7324. https://doi.org/10.1523/jneurosci.0025-16.2016

Geisler, W. S., & Kersten, D. (2002). Illusions, perception and Bayes. *Nature Neuroscience*, *5*(6), 508–510. https://doi.org/10.1038/nn0602-508

Goodale, M. A., & Milner, A. D. (1992, January). Separate visual pathways for perception and action. *Trends in Neurosciences*. https://doi.org/10.1016/0166-2236(92)90344-8

Grübel, J., Weibel, R., Jiang, M. H., Hölscher, C., Hackman, D. A., & Schinazi, V. R. (2017). EVE: A framework for experiments in virtual environments. In *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* (Vol. 10523 LNAI, pp. 159–176). Springer, Cham. https://doi.org/10.1007/978-3-319-68189-4_10

Harjunen, V. J., Ahmed, I., Jacucci, G., Ravaja, N., & Spapé, M. M. (2017). Manipulating Bodily Presence Affects Cross-Modal Spatial Attention: A Virtual-Reality-Based ERP Study. *Frontiers in Human Neuroscience*, *11*(February), 1–12. https://doi.org/10.3389/fnhum.2017.00079

Herwig, A. (2015, May). Linking perception and action by structure or process? Toward an integrative perspective. *Neuroscience and Biobehavioral Reviews*.

https://doi.org/10.1016/j.neubiorev.2015.02.013

Hisakata, R., Terao, M., & Murakami, I. (2013). Illusory position shift induced by motion within a moving envelope during smooth-pursuit eye movements. *Journal of Vision*, *13*(12), 21–21. https://doi.org/10.1167/13.12.21

Hisakata, Rumi, & Murakami, I. (2009). Illusory position shift induced by plaid motion. *Vision Research*, *49*(24), 2902–2910. https://doi.org/10.1016/j.visres.2009.09.009

Hoffman, D. D. (2018). The Interface Theory of Perception. In J. T. Wixted & J. T. Serences (Eds.), *Stevens' Handbook of Experimental Psychology and Cognitive Neuroscience - Volume 2* (4th ed., pp. 731–754). Hoboken, NJ, USA: John Wiley & Sons, Inc. https://doi.org/10.1002/9781119170174.epcn216

Hubel, D. H., & Wiesel, T. N. (1968). Receptive fields and functional architecture of monkey striate cortex. *The Journal of Physiology*, *195*(1), 215–243. https://doi.org/10.1113/jphysiol.1968.sp008455

Jogan, M., & Stocker, A. A. (2015). Signal Integration in Human Visual Speed Perception. *Journal of Neuroscience*, *35*(25), 9381–9390. https://doi.org/10.1523/jneurosci.4801-14.2015

Kalman, R. E. (2011). A New Approach to Linear Filtering and Prediction Problems. *Journal of Basic Engineering*, *82*(1), 35. https://doi.org/10.1115/1.3662552

Kerzel, D., & Gegenfurtner, K. R. (2005). Motion-induced illusory displacement reexamined: Differences between perception and action? *Experimental Brain Research*, *162*(2), 191–201. https://doi.org/10.1007/s00221-004-2139-z

Kitaoka, A., & Ashida, H. (2003). Phenomenal characteristics of the peripheral drift illusion. *Vision*, *15*(4), 261–262.

Kohler, P. J., Cavanagh, P., & Tse, P. U. (2015). Motion-induced position shifts are influenced by global motion, but dominated by component motion. *Vision Research*, *110*(Part A), 93–99. https://doi.org/10.1016/j.visres.2015.03.003

Kopiske, K. K., Bruno, N., Hesse, C., Schenk, T., & Franz, V. H. (2016). The functional subdivision of the visual brain: Is there a real illusion effect on action? A multi-lab replication study. *Cortex*, *79*(April), 130–152. https://doi.org/10.1016/j.cortex.2016.03.020

Kosovicheva, A. A., Wolfe, B. A., & Whitney, D. (2014). Visual motion shifts saccade targets. *Attention, Perception, and Psychophysics*, *76*(6), 1778–1788. https://doi.org/10.3758/s13414-014-0680-9

Kwon, O.-S., Tadin, D., & Knill, D. C. (2015). Unifying account of visual motion and position perception. *Proceedings of the National Academy of Sciences*, *112*(26), 8142–8147. https://doi.org/10.1073/pnas.1500361112

Laitin, E. L., Tymoski, M. J., Tenhundfeld, N. L., & Witt, J. K. (2019). The uphill battle for action-specific perception. *Attention, Perception, and Psychophysics*, *81*(3), 778–793. https://doi.org/10.3758/s13414-018-01652-w

Linares, D., López-Moliner, J., & Johnston, A. (2007). Motion signal and the perceived positions of moving objects. *Journal of Vision*, *7*(7), 1. https://doi.org/10.1167/7.7.1

Lisi, M., & Cavanagh, P. (2015). Dissociation between the perceptual and saccadic localization of moving objects. *Current Biology*, *25*(19), 2535–2540. https://doi.org/10.1016/j.cub.2015.08.021

Maloney, R. T., Clifford, C. W. G., & Mareschal, I. (2018). Directional Limits on Motion Transparency Assessed Through Colour-Motion Binding. *Perception*, *47*(3), 254–275. https://doi.org/10.1177/0301006617745010

Marinovic, W., Plooy, A. M., & Arnold, D. H. (2012). The influence of visual motion on interceptive actions and perception. *Vision Research*, *60*, 73–78. https://doi.org/10.1016/j.visres.2012.03.010

Mather, G., & Pavan, A. (2009). Motion-induced position shifts occur after motion integration. *Vision Research*, *49*(23), 2741–2746.

https://doi.org/10.1016/j.visres.2009.07.016

Maus, G. W., Fischer, J., & Whitney, D. (2013). Motion-dependent representation of space in area MT+. *Neuron*, *78*(3), 554–562. https://doi.org/10.1016/j.neuron.2013.03.010

McGraw, P. V, Whitaker, D., Skillen, J., & Chung, S. T. L. (2002). Motion adaptation distorts perceived visual position. *Current Biology*, *12*(23), 2042–2047. https://doi.org/10.1016/S0960-9822(02)01354-4

Medendorp, W. P., de Brouwer, A. J., & Smeets, J. B. J. (2018). Dynamic representations of visual space for perception and action. *Cortex*, *98*, 194–202. https://doi.org/10.1016/j.cortex.2016.11.013

Movshon, J. A., Adelson, E. H., Gizzi, M. S., & Newsome, W. T. (1983). The Analysis of Moving Visual Patterns. In Chagas C., Gattass R., & Gross C. (Eds.), *Pattern recognition mechanisms* (pp. 117–151). Rome: Vatican Press. https://doi.org/10.1007/978-3-662-09224-8_7

Nakayama, K. (1985, November). Biological image motion processing: A review. *Vision Research*. https://doi.org/10.1016/0042-6989(85)90171-3

Nishida, S. (2011). Advancement of motion psychophysics: review 2001-2010. *Journal of Vision*, *11*(5), 11. https://doi.org/10.1167/11.5.11

Nishida, S., & Johnston, A. (1999). Influence of motion signals on the perceived position of spatial pattern. *Nature*, *397*(6720), 610–612. https://doi.org/10.1038/17600

Nour, M. M., & Nour, J. M. (2015). Perception, illusions and Bayesian inference. *Psychopathology*, *48*(4), 217–221. https://doi.org/10.1159/000437271

Park, W. J., & Tadin, D. (2018). Motion Perception. In J. T. Wixted & J. T. Serences (Eds.), *Stevens' Handbook of Experimental Psychology and Cognitive Neuroscience* - *Volume 2* (4th ed., pp. 415–488). Hoboken, NJ, USA: John Wiley & Sons, Inc. https://doi.org/10.1002/9781119170174.epcn210

Parker, M. G., Tyson, S. F., Weightman, A. P., Abbott, B., Emsley, R., & Mansell, W.

(2017). Perceptual control models of pursuit manual tracking demonstrate individual specificity and parameter consistency. *Attention, Perception, and Psychophysics*, *79*(8), 2523–2537. https://doi.org/10.3758/s13414-017-1398-2

Pattadkal, J. J., Mato, G., van Vreeswijk, C., Priebe, N. J., & Hansel, D. (2018). Emergent Orientation Selectivity from Random Networks in Mouse Visual Cortex. *Cell Reports*, *24*(8), 2042-2050.e6. https://doi.org/10.1016/j.celrep.2018.07.054

Pavan, A., & Mather, G. (2008). Distinct position assignment mechanisms revealed by cross-order motion. *Vision Research*, *48*(21), 2260–2268. https://doi.org/10.1016/j.visres.2008.07.001

Pizlo, Z. (2001). Perception viewed as an inverse problem. *Vision Research*, *41*(24), 3145–3161. https://doi.org/10.1016/S0042-6989(01)00173-0

Ramachandran, V. S., & Anstis, S. M. (1986). The Perception of Apparent Motion. *Scientific American*, *254*(6), 102–109.

Ramachandran, V. S., & Anstis, S. M. (1990). Illusory displacement of equiluminous kinetic edges. *Perception*, *19*(5), 611–616. https://doi.org/10.1068/p190611

Readinger, W. O., Chatziastros, A., Cunningham, D. W., Bülthoff, H. H., & Cutting, J. E. (2002). Gaze-eccentricity effects on road position and steering. *Journal of Experimental Psychology: Applied*, *8*(4), 247–258. https://doi.org/10.1037/1076-898X.8.4.247

Renner, R. S., Velichkovsky, B. M., & Helmert, J. R. (2014). The perception of egocentric distances in virtual environments - A review. *ACM Computing Surveys*, *46*(2), 1–40. https://doi.org/10.1145/2543581.2543590

Rocchi, F., Ledgeway, T., & Webb, B. S. (2018). Criterion-free measurement of motion transparency perception at different speeds. *Journal of Vision*, *18*(4), 5. https://doi.org/10.1167/18.4.5

Rushton, S. K., & Duke, P. A. (2009). Observers cannot accurately estimate the speed of an approaching object in flight. *Vision Research*, *49*(15), 1919–1928.

https://doi.org/10.1016/j.visres.2008.12.012

Scarfe, P., & Glennerster, A. (2015). Using high-fidelity virtual reality to study perception in freely moving observers. *Journal of Vision*, *15*(9), 3. https://doi.org/10.1167/15.9.3

Shapiro, A., Lu, Z. L., Huang, C. B., Knight, E., & Ennis, R. (2010). Transitions between central and peripheral vision create spatial/temporal distortions: A hypothesis concerning the perceived break of the curveball. *PLoS ONE*, *5*(10), e13296. https://doi.org/10.1371/journal.pone.0013296

Soon, C. S., Dubey, R., Ananyev, E., & Hsieh, P.-J. (2017). Approaches to Understanding Visual Illusions. In Q. Zhao (Ed.), *Computational and Cognitive Neuroscience of Vision* (1st ed., pp. 221–233). Singapore: Springer Singapore. https://doi.org/10.1007/978-981-10-0213-7_10

Sotiropoulos, G., Seitz, A. R., & Seriès, P. (2014). Contrast dependency and prior expectations in human speed perception. *Vision Research*, *97*, 16–23. https://doi.org/10.1016/j.visres.2014.01.012

Spanlang, B., Normand, J.-M., Borland, D., Kilteni, K., Giannopoulos, E., PomÃ©s, A. s, … Slater, M. (2014). How to Build an Embodiment Lab: Achieving Body Representation Illusions in Virtual Reality. *Frontiers in Robotics and AI*, *1*, 9. https://doi.org/10.3389/frobt.2014.00009

Stocker, A. A., & Simoncelli, E. P. (2006). Noise characteristics and prior expectations in human visual speed perception. *Nature Neuroscience*, *9*(4), 578–585. https://doi.org/10.1038/nn1669

Stone, L. S., & Thompson, P. (1992). Human speed perception is contrast dependent. *Vision Research*, *32*(8), 1535–1549. https://doi.org/10.1016/0042-6989(92)90209-2

Temme, L. A., Kalich, M. E., Curry, I. P., Pinkus, A. R., & Lee, H.-J. (2009). Visual Perceptual Conflicts and Illusions. In C. E. Rash, M. B. Russo, T. R. Letowski, & E. T. Schmeisser (Eds.), *Helmet-Mounted Displays: Sensation, Perception and Cognitive*

Issues (pp. 491–578). US Army Aeromedical Research Laboratory, Fort Rucker, AL.

Tse, P. U., & Hsieh, P. J. (2006). The infinite regress illusion reveals faulty integration of local and global motion signals. *Vision Research*, *46*(22), 3881–3885. https://doi.org/10.1016/j.visres.2006.06.010

Tsui, S. Y., Khuu, S. K., & Hayes, A. (2007). Apparent position in depth of stationary moving three-dimensional objects. *Vision Research*, *47*(1), 8–15. https://doi.org/10.1016/j.visres.2006.09.004

Ueda, H., Abekawa, N., & Gomi, H. (2018). The faster you decide, the more accurate localization is possible: Position representation of “curveball illusion” in perception and eye movements. *PLoS ONE*, *13*(8), e0201610. https://doi.org/10.1371/journal.pone.0201610

van Heusden, E., Rolfs, M., Cavanagh, P., & Hogendoorn, H. (2018). Motion Extrapolation for Eye Movements Predicts Perceived Motion-Induced Position Shifts. *The Journal of Neuroscience*, *38*(38), 8243–8250. https://doi.org/10.1523/jneurosci.0736-18.2018

Vasser, M., Kängsepp, M., Magomedkerimov, M., Kilvits, K., Stafinjak, V., Kivisik, T., … Aru, J. (2017). VREX: an open-source toolbox for creating 3D virtual reality experiments. *BMC Psychology*, *5*(1), 4. https://doi.org/10.1186/s40359-017-0173-4

Verstraten, F. A. ., Cavanagh, P., & Labianca, A. T. (2000). Limits of attentive tracking reveal temporal properties of attention. *Vision Research*, *40*(26), 3651–3664. https://doi.org/10.1016/S0042-6989(00)00213-3

Veto, P., Uhlig, M., Troje, N. F., & Einhäuser, W. (2018). Cognition modulates action-to-perception transfer in ambiguous perception. *Journal of Vision*, *18*(8), 5. https://doi.org/10.1167/18.8.5

von Helmholtz, H. (1924). *Treatise on physiological optics. Volume III (Trans. from the 3rd German ed.).* (J. P. C. Southall, Ed.). Rochester: Optical Society of America. https://doi.org/10.1037/13536-000

Warren, P. A., & Rushton, S. K. (2009). Optic Flow Processing for the Assessment of Object Movement during Ego Movement. *Current Biology*, *19*(18), 1555–1560. https://doi.org/10.1016/j.cub.2009.07.057

Watanabe, E., Kitaoka, A., Sakamoto, K., Yasugi, M., & Tanaka, K. (2018). Illusory motion reproduced by deep neural networks trained for prediction. *Frontiers in Psychology*, *9*(MAR), 345. https://doi.org/10.3389/fpsyg.2018.00345

Watanabe, K. (2005). The motion-induced position shift depends on the visual awareness of motion. *Vision Research*, *45*(19), 2580–2586. https://doi.org/10.1016/j.visres.2005.03.001

Weibel, R. P., Grübel, J., Zhao, H., Thrash, T., Meloni, D., Hölscher, C., & Schinazi, V. R. (2018). Virtual Reality Experiments with Physiological Measures. *Journal of Visualized Experiments*, (138). https://doi.org/10.3791/58318

Weiss, Y., Simoncelli, E. P., & Adelson, E. H. (2002). Motion illusions as optimal percepts. *Nature Neuroscience*, *5*(6). https://doi.org/10.1038/nn858

Westfall, J., Kenny, D. A., & Judd, C. M. (2014). Statistical power and optimal design in experiments in which samples of participants respond to samples of stimuli. *Journal of Experimental Psychology. General*, *143*(5), 2020–2045. https://doi.org/10.1037/xge0000014

Whitney, D. (2002). The influence of visual motion on perceived position. *Trends in Cognitive Sciences*, *6*(5), 211–216.

Whitney, D., & Cavanagh, P. (2000). Motion distorts visual space: Shifting the perceived position of remote stationary objects. *Nature Neuroscience*, *3*(9), 954–959. https://doi.org/10.1038/78878

Whitney, D., Goltz, H. C., Thomas, C. G., Gati, J. S., Menon, R. S., & Goodale, M. A. (2003). Flexible Retinotopy: Motion-Dependent Position Coding in the Visual Cortex. *Science*, *302*(5646), 878–881. https://doi.org/10.1126/science.1087839

Wickens, C. D. (2014). Effort in human factors performance and decision making. *Human Factors*, *56*(8), 1329–1336. https://doi.org/10.1177/0018720814558419

Wilson, C. J., & Soranzo, A. (2015). The Use of Virtual Reality in Psychology: A Case Study in Visual Perception. *Computational and Mathematical Methods in Medicine*, *2015*, 1–7. https://doi.org/10.1155/2015/151702

Witt, J. K. (2018). Perception and Action. In J. T. Wixted & J. T. Serences (Eds.), *Stevens' Handbook of Experimental Psychology and Cognitive Neuroscience Vol 2* (4th ed., pp. 489–523). Hoboken, NJ, USA: John Wiley & Sons, Inc. https://doi.org/10.1002/9781119170174.epcn211

Witt, J. K., Linkenauger, S. A., & Wickens, C. (2016). Action-specific effects in perception and their potential applications. *Journal of Applied Research in Memory and Cognition*, *5*(1), 69–76. https://doi.org/10.1016/j.jarmac.2015.07.008

Yamagishi, N., Anderson, S. J., & Ashida, H. (2001). Evidence for dissociation between the perceptual and visuomotor systems in humans. *Proceedings of the Royal Society B: Biological Sciences*, *268*(1470), 973–977. https://doi.org/10.1098/rspb.2001.1603

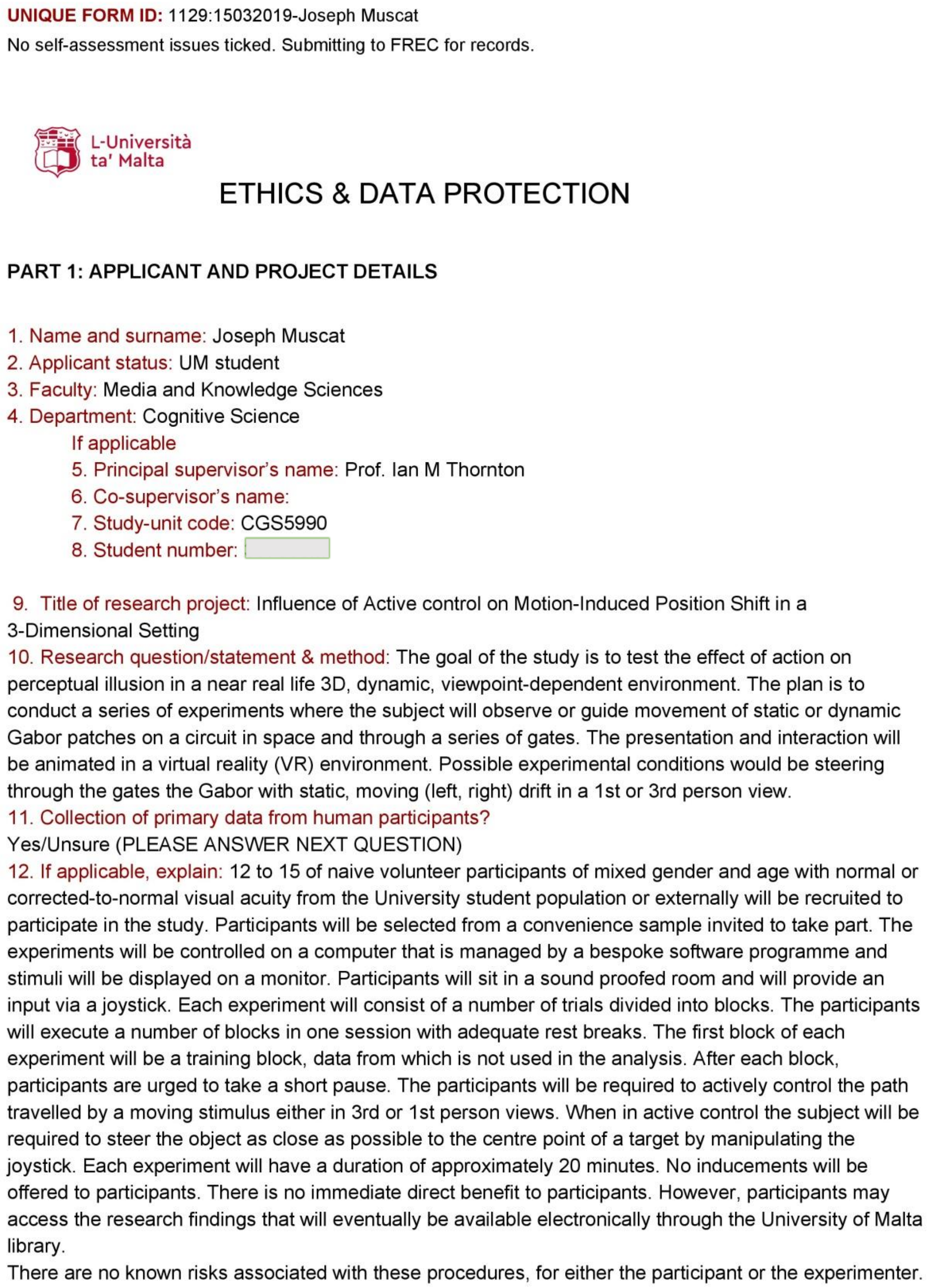
Ye, M., Wang, Q., Peng, X., An, J., Chen, Y., Ye, F., & Wang, D. (2018). Motion-induced position shift in early Alzheimer's disease. *Scientific Reports*, *8*(1), 9833. https://doi.org/10.1038/s41598-018-27991-0

Zeki, S. M. (1974). Functional organization of a visual area in the posterior bank of the superior temporal sulcus of the rhesus monkey. *The Journal of Physiology*, *236*(3), 549–573. https://doi.org/10.1113/jphysiol.1974.sp010452

Zhao, H., Thrash, T., Wehrli, S., Hölscher, C., Kapadia, M., Grübel, J., … Schinazi, V. R. (2018). A networked desktop virtual reality setup for decision science and navigation experiments with multiple participants. *Journal of Visualized Experiments*, (138). https://doi.org/10.3791/58155

Zimmermann, E., Morrone, M. C., & Burr, D. (2012). Visual motion distorts visual and motor space. *Journal of Vision*, *12*(2), 10–10. https://doi.org/10.1167/12.2.10

Appendix A – Ethics & Data Protection submission



UNIQUE FORM ID: 1129:15032019-Joseph Muscat
No self-assessment issues ticked. Submitting to FREC for records.

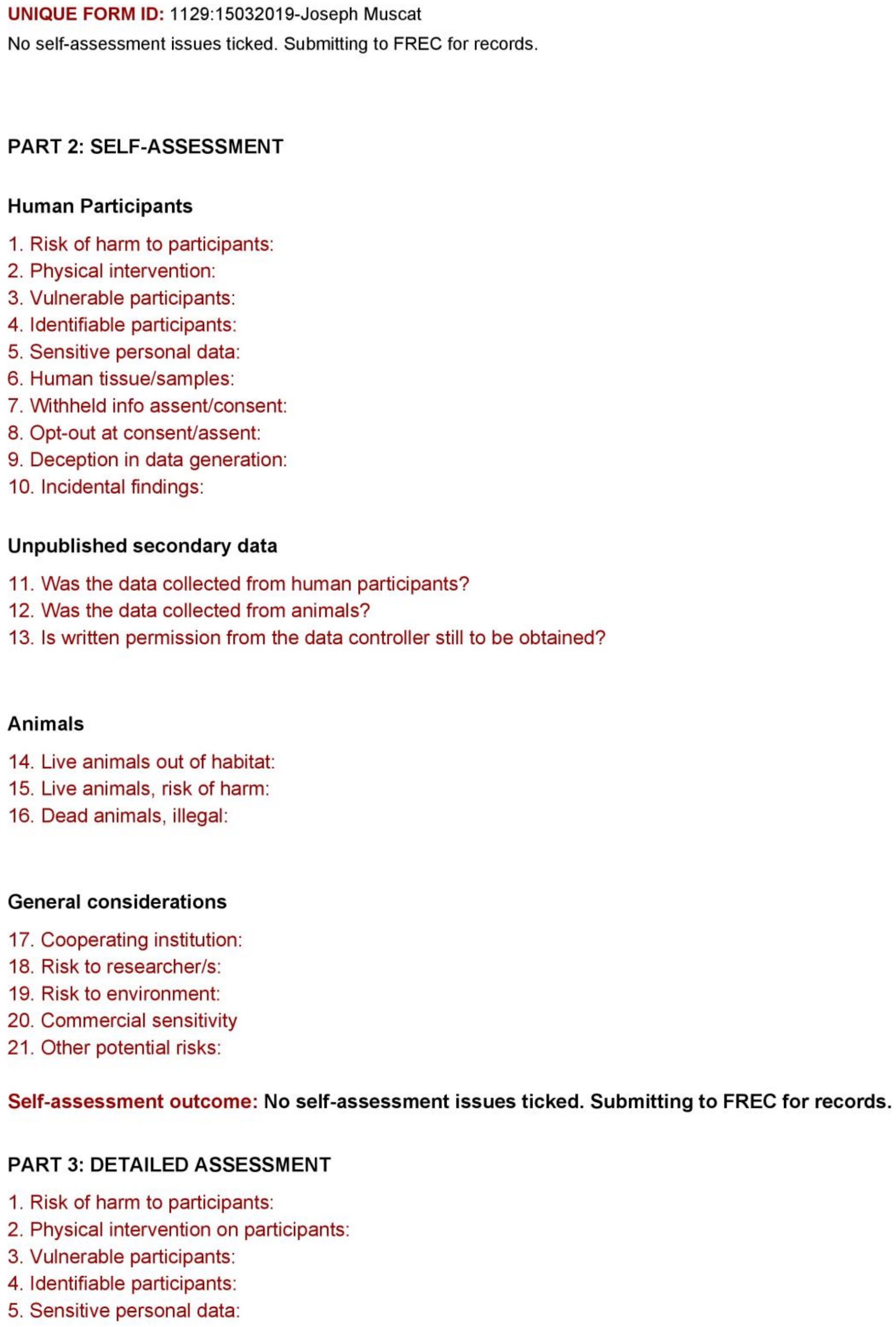
L-Università
ta' Malta

ETHICS & DATA PROTECTION

PART 1: APPLICANT AND PROJECT DETAILS

1. Name and surname: Joseph Muscat
2. Applicant status: UM student
3. Faculty: Media and Knowledge Sciences
4. Department: Cognitive Science
    If applicable
    5. Principal supervisor's name: Prof. Ian M Thornton
    6. Co-supervisor's name:
    7. Study-unit code: CGS5990
    8. Student number: [redacted]

9. Title of research project: Influence of Active control on Motion-Induced Position Shift in a 3-Dimensional Setting
10. Research question/statement & method: The goal of the study is to test the effect of action on perceptual illusion in a near real life 3D, dynamic, viewpoint-dependent environment. The plan is to conduct a series of experiments where the subject will observe or guide movement of static or dynamic Gabor patches on a circuit in space and through a series of gates. The presentation and interaction will be animated in a virtual reality (VR) environment. Possible experimental conditions would be steering through the gates the Gabor with static, moving (left, right) drift in a 1st or 3rd person view.
11. Collection of primary data from human participants?
Yes/Unsure (PLEASE ANSWER NEXT QUESTION)
12. If applicable, explain: 12 to 15 of naive volunteer participants of mixed gender and age with normal or corrected-to-normal visual acuity from the University student population or externally will be recruited to participate in the study. Participants will be selected from a convenience sample invited to take part. The experiments will be controlled on a computer that is managed by a bespoke software programme and stimuli will be displayed on a monitor. Participants will sit in a sound proofed room and will provide an input via a joystick. Each experiment will consist of a number of trials divided into blocks. The participants will execute a number of blocks in one session with adequate rest breaks. The first block of each experiment will be a training block, data from which is not used in the analysis. After each block, participants are urged to take a short pause. The participants will be required to actively control the path travelled by a moving stimulus either in 3rd or 1st person views. When in active control the subject will be required to steer the object as close as possible to the centre point of a target by manipulating the joystick. Each experiment will have a duration of approximately 20 minutes. No inducements will be offered to participants. There is no immediate direct benefit to participants. However, participants may access the research findings that will eventually be available electronically through the University of Malta library.
There are no known risks associated with these procedures, for either the participant or the experimenter.



UNIQUE FORM ID: 1129:15032019-Joseph Muscat

No self-assessment issues ticked. Submitting to FREC for records.

PART 2: SELF-ASSESSMENT

Human Participants

1. Risk of harm to participants:
2. Physical intervention:
3. Vulnerable participants:
4. Identifiable participants:
5. Sensitive personal data:
6. Human tissue/samples:
7. Withheld info assent/consent:
8. Opt-out at consent/assent:
9. Deception in data generation:
10. Incidental findings:

Unpublished secondary data

11. Was the data collected from human participants?
12. Was the data collected from animals?
13. Is written permission from the data controller still to be obtained?

Animals

14. Live animals out of habitat:
15. Live animals, risk of harm:
16. Dead animals, illegal:

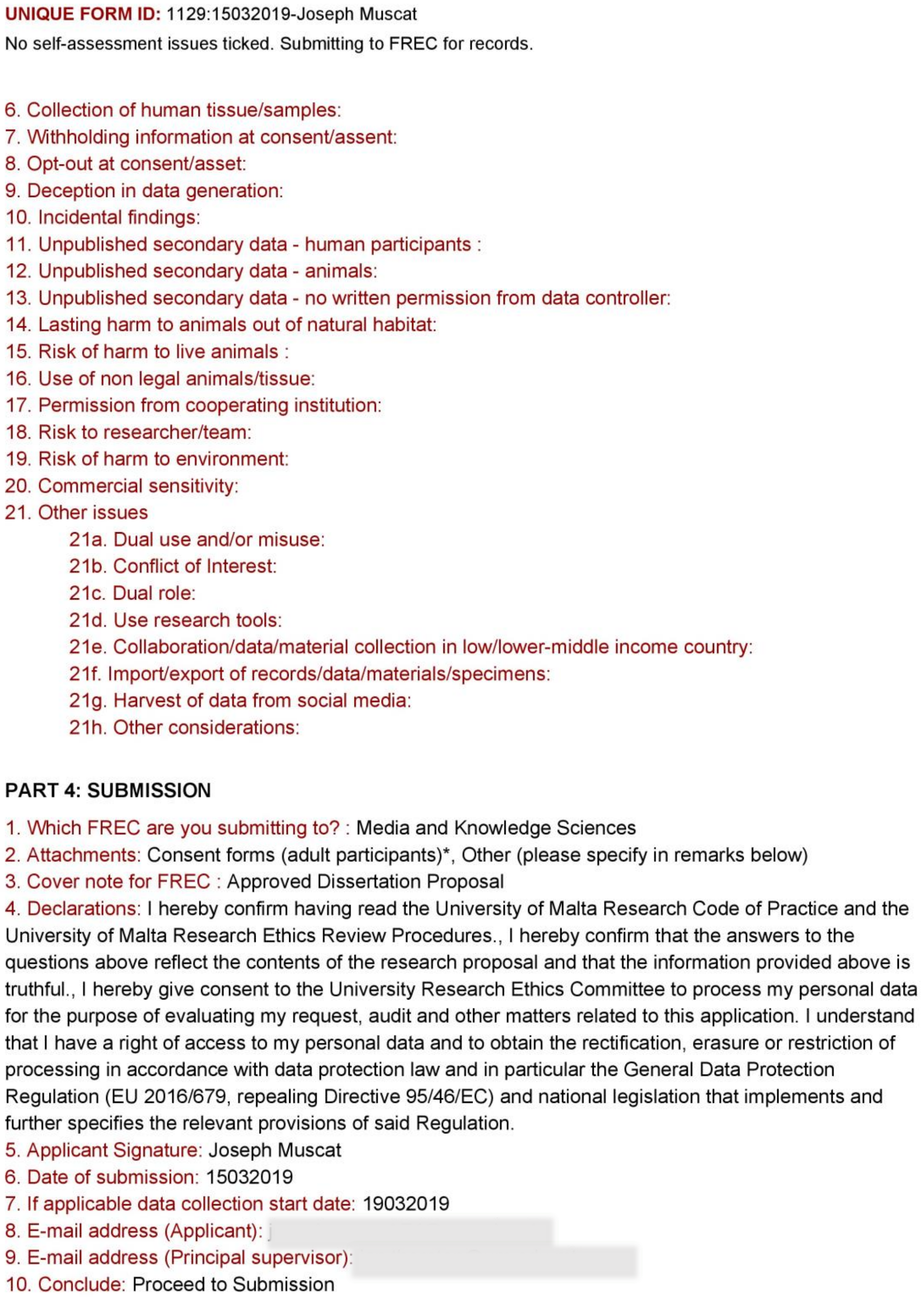
General considerations

17. Cooperating institution:
18. Risk to researcher/s:
19. Risk to environment:
20. Commercial sensitivity
21. Other potential risks:

Self-assessment outcome: **No self-assessment issues ticked. Submitting to FREC for records.**

PART 3: DETAILED ASSESSMENT

1. Risk of harm to participants:
2. Physical intervention on participants:
3. Vulnerable participants:
4. Identifiable participants:
5. Sensitive personal data:



UNIQUE FORM ID: 1129:15032019-Joseph Muscat

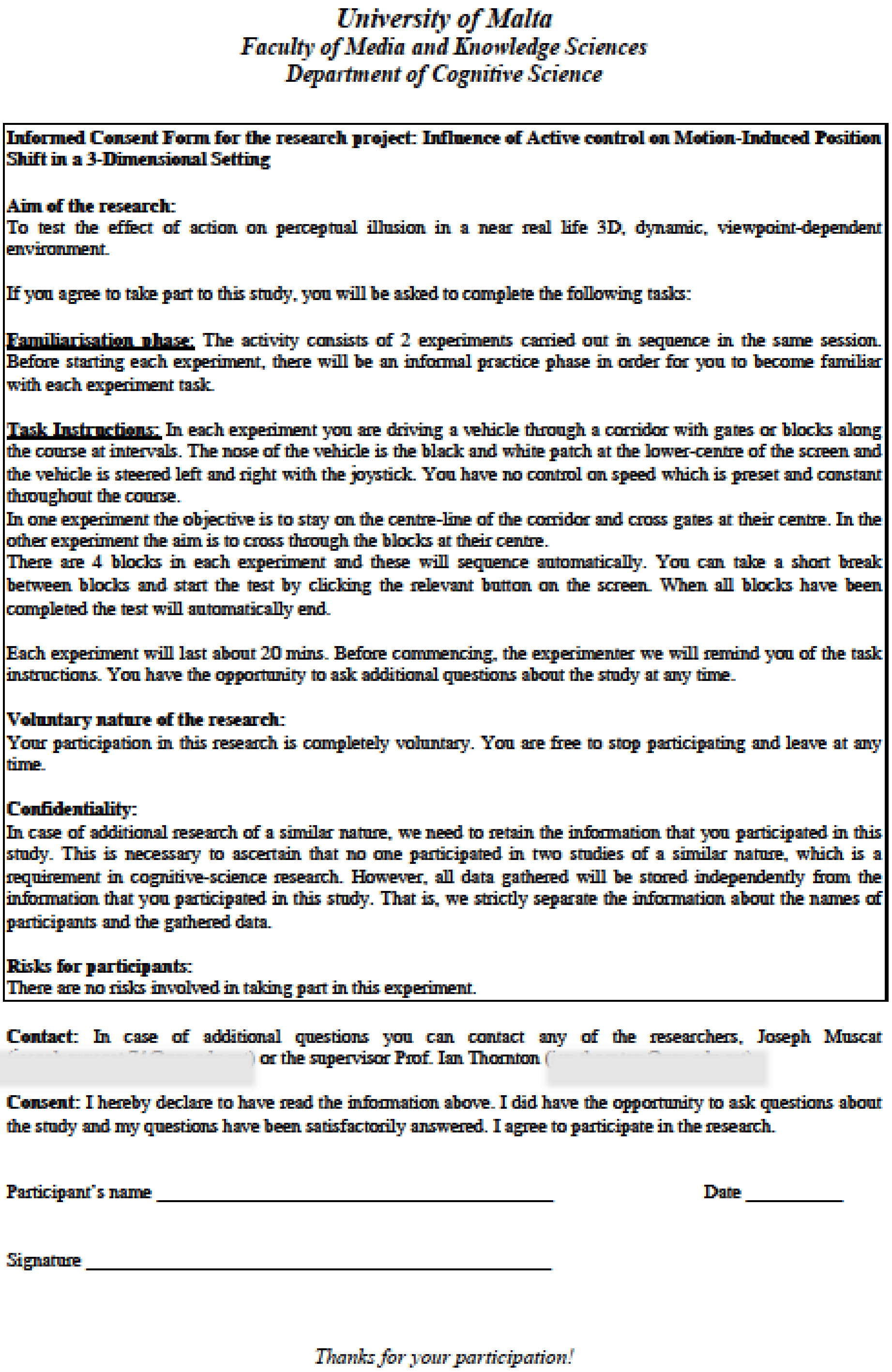
No self-assessment issues ticked. Submitting to FREC for records.

6. Collection of human tissue/samples:
7. Withholding information at consent/assent:
8. Opt-out at consent/asset:
9. Deception in data generation:
10. Incidental findings:
11. Unpublished secondary data - human participants :
12. Unpublished secondary data - animals:
13. Unpublished secondary data - no written permission from data controller:
14. Lasting harm to animals out of natural habitat:
15. Risk of harm to live animals :
16. Use of non legal animals/tissue:
17. Permission from cooperating institution:
18. Risk to researcher/team:
19. Risk of harm to environment:
20. Commercial sensitivity:
21. Other issues
    - 21a. Dual use and/or misuse:
    - 21b. Conflict of Interest:
    - 21c. Dual role:
    - 21d. Use research tools:
    - 21e. Collaboration/data/material collection in low/lower-middle income country:
    - 21f. Import/export of records/data/materials/specimens:
    - 21g. Harvest of data from social media:
    - 21h. Other considerations:

PART 4: SUBMISSION

1. Which FREC are you submitting to? : Media and Knowledge Sciences
2. Attachments: Consent forms (adult participants)*, Other (please specify in remarks below)
3. Cover note for FREC : Approved Dissertation Proposal
4. Declarations: I hereby confirm having read the University of Malta Research Code of Practice and the University of Malta Research Ethics Review Procedures., I hereby confirm that the answers to the questions above reflect the contents of the research proposal and that the information provided above is truthful., I hereby give consent to the University Research Ethics Committee to process my personal data for the purpose of evaluating my request, audit and other matters related to this application. I understand that I have a right of access to my personal data and to obtain the rectification, erasure or restriction of processing in accordance with data protection law and in particular the General Data Protection Regulation (EU 2016/679, repealing Directive 95/46/EC) and national legislation that implements and further specifies the relevant provisions of said Regulation.
5. Applicant Signature: Joseph Muscat
6. Date of submission: 15032019
7. If applicable data collection start date: 19032019
8. E-mail address (Applicant): [redacted]
9. E-mail address (Principal supervisor): [redacted]
10. Conclude: Proceed to Submission

Appendix B – Information and Consent sheet



University of Malta
Faculty of Media and Knowledge Sciences
Department of Cognitive Science

Informed Consent Form for the research project: Influence of Active control on Motion-Induced Position Shift in a 3-Dimensional Setting

Aim of the research:
To test the effect of action on perceptual illusion in a near real life 3D, dynamic, viewpoint-dependent environment.

If you agree to take part to this study, you will be asked to complete the following tasks:

Familiarisation phase: The activity consists of 2 experiments carried out in sequence in the same session. Before starting each experiment, there will be an informal practice phase in order for you to become familiar with each experiment task.

Task Instructions: In each experiment you are driving a vehicle through a corridor with gates or blocks along the course at intervals. The nose of the vehicle is the black and white patch at the lower-centre of the screen and the vehicle is steered left and right with the joystick. You have no control on speed which is preset and constant throughout the course.
In one experiment the objective is to stay on the centre-line of the corridor and cross gates at their centre. In the other experiment the aim is to cross through the blocks at their centre.
There are 4 blocks in each experiment and these will sequence automatically. You can take a short break between blocks and start the test by clicking the relevant button on the screen. When all blocks have been completed the test will automatically end.

Each experiment will last about 20 mins. Before commencing, the experimenter we will remind you of the task instructions. You have the opportunity to ask additional questions about the study at any time.

Voluntary nature of the research:
Your participation in this research is completely voluntary. You are free to stop participating and leave at any time.

Confidentiality:
In case of additional research of a similar nature, we need to retain the information that you participated in this study. This is necessary to ascertain that no one participated in two studies of a similar nature, which is a requirement in cognitive-science research. However, all data gathered will be stored independently from the information that you participated in this study. That is, we strictly separate the information about the names of participants and the gathered data.

Risks for participants:
There are no risks involved in taking part in this experiment.

Contact: In case of additional questions you can contact any of the researchers, Joseph Muscat [redacted] or the supervisor Prof. Ian Thornton [redacted]

Consent: I hereby declare to have read the information above. I did have the opportunity to ask questions about the study and my questions have been satisfactorily answered. I agree to participate in the research.

Participant's name ________________________ Date __________

Signature ________________________

Thanks for your participation!