AN INVESTIGATION INTO THE DIRECTIONAL AND AMPLITUDE ASPECTS OF AN INTERNAL MODEL OF GRAVITY

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AN INVESTIGATION INTO THE DIRECTIONAL AND AMPLITUDE ASPECTS OF AN INTERNAL MODEL OF GRAVITY

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Thesis Abstract

Studies of interception have shown that participants expect free-falling targets to descend vertically and accelerate at g (9.81 m/s^2). Visuomotor delays render motor commands obsolete in such rapidly changing situations, so predictive control is necessary. Internal models have been proposed as a mechanism to predict the future position of free-falling objects. Internal models are predictive systems that provide input to the motor and sensory systems, and are acquired by the CNS from experience.

The overall aim of this thesis was to investigate the existence of a possible internal model of gravity and to explore its directional and acceleration amplitude aspects. This thesis is the first study to investigate directional and amplitude aspects of such a model by systematically varying stimulus target kinematics.

In the first two experiments, participants performed visually guided tracking of realistic virtual stimuli. In experiment 1, stimuli accelerated at g but moved in different straight-line directions. In experiment 2, stimuli always descended vertically but with different accelerations (as percentages of g). Tracking was by finger pointing, laser pointing, gaze tracking in isolation or gaze tracking with concomitant manual or laser tracking. In the absence of on-screen feedback of indicated position (i.e. non-laser trials), tracking was generally tuned for targets that **a)** descended vertically (or tended increasingly to vertically downwards over time) and **b)** accelerated at g or slightly less than g.

In the third experiment, participants judged whether a target accelerating at g was moving vertically, or to the left or right of the vertical. The stimuli from experiment 1 were used. I found that **a)** participants' reports were influenced by an expectation that gravity would affect the trajectory even when there is visual information to the contrary (i.e. an effect of gravity was expected on observed trajectory); and **b)** physics expertise yielded no difference in performance suggesting that performance, based on an internal model of gravity, is determined by experience of seeing things fall in the real-world under gravity, rather than by intellectual understanding of gravity. In the fourth experiment, participants judged whether a target accelerated at less than g, at g, or greater than g. The stimuli from experiment 2 were used. As with experiment 3, I found no effect of physics expertise and only weak evidence in support of an internal model of gravity.

I conclude that the CNS is likely construct and maintain an internal model of gravity that predicts the future position of free-falling targets to be in a 'real-world'

manner – acceleration at 99% or 100% of *g* and vertically downwards or in a direction tending increasingly to vertically downwards over time. I found no evidence for 'direct perception' (observation yielding first-order time-to-contact information). In the final conclusion I briefly discuss alternative possibilities for predictive motor control.

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Sincerely,

Jonathan Charles Flavell

Authors Declaration

The work in this thesis was carried out in accordance with the regulations of the Manchester Metropolitan University. The work is original and no part of this thesis has been submitted for any other academic award.

Aside from writing this thesis, the author's involvement in the project included:

- Deciding upon the conditions and parameters used in each experiment.
- Arranging laboratory equipment for optimal capture and setting up the laboratory for each experimental session.
- Sole responsibility for set-up, calibration and operation of all equipment in experimental sessions following tuition by Dr. Emma Tole on the use of Vicon hardware and Nexus software, and tuition by Professor Dilwyn Marple-Horvat on the use of the ASL eye tracker.
- Selection and execution of statistical tests using either standard methods in SPSS or similar methods in MATLAB using Mathworks® functions. All other analysis was carried out using MATLAB scripts and functions that were designed, written, and executed by the author unless otherwise stated (see below).

The following assistance was received in completing the work:

- Design of the experimental paradigm was a collaboration between Jonathan Flavell and Professor Ian Loram and Professor Dilwyn Marple-Horvat.
- Interpretation of output was principally by the author with contributions from Professor Ian Loram and Professor Dilwyn Marple-Horvat.
- Professor Dilwyn Marple-Horvat selected and procured the projector and projection screen and taught the author use and technical aspects of the ASL 501 eye tracker.
- Professor Ian Loram provided a MATLAB script to read .c3d files.
- Dr. Linda Tersteeg provided a Matlab script that transforms horizontal and vertical eye-in-orbit rotations from volts to degrees using static calibration.

- Des Richards built an analogue signal output box and provided technical advice.

Any views expressed in this thesis are those of the author and do not necessarily represent those of Manchester Metropolitan University.

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Presentations

Flavell, JC, Loram, IL, Marple-Horvat, DE. Pointing at and tracking falling targets: directional aspects of an internal model of gravity. IUPS, 2013.

Flavell, JC, Loram, IL, Marple-Horvat, DE. Internal models of familiar motion. MMU Annual Student Research Conference, 2011.

Flavell, JC, Loram, IL, Marple-Horvat, DE. An investigation of pre-existing internal models of gravity. 6th North West Biomechanics Research Day, 2011.

Flavell, JC, Loram, IL, Marple-Horvat, DE. Visuomotor control & internal models of familiar motion in the real world. MMU Annual Student Research Conference, 2010.

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CHAPTER 1
INTRODUCTION TO THE THESIS

1.1 General introduction

All over the world cultures have developed ball games in which a key aspect of success is a player's interception of free-falling objects e.g. cricket by the English, baseball by the Americans, Lapta by the Russians, Takraw by the Thai, Ki oh Rahi by the Maori, Mer Kai by the Aborigines, and Kemari by the Japanese. Aside from drag aspects of certain objects, such as shuttlecocks, the primary influence on the movement of free-falling targets is gravity. Earth's gravity is accepted as 9.81 m/s^2 (g) and varies little around the world. It is weaker at the equator than at the poles by approximately 0.5 % because of a combination of the Earth's oblate shape and rotational speed. There is also approximately a 0.28 % decrease in gravity at 8,848 m above sea level, though games are seldom played on the top of Mount Everest.

Despite rapid acceleration due to gravity, most people are usually able to intercept free-falling targets and initiate grasping at a time that avoids targets colliding with the outside of the fingers (grasping too early) or bouncing out of the hand (grasping too late). This is remarkable given that visuomotor delays of typically 150-200ms (Zago, McIntyre, Senot, & Lacquaniti, 2008) will render motor commands obsolete in rapidly changing situations – during that time a free-falling object seen at one location will have moved a considerable distance along its trajectory as an interception movement begins. A prediction of future target position is therefore necessary.

Firstly a description of the processes capable of prediction is given. Following this is a review of internal modelling of gravity. I then outline the major sections of this thesis.

1.2 Predicting the future

1.2.1 Internal models

Internal models are currently a prominent theory in motor control. These models represent predictive systems that provide input to the motor and sensory systems. There is thought to be an *inverse* and a *forward* model of the motor system. The inverse model captures the inverse dynamics of a limb, or object, being controlled allowing optimal control with low mechanical stiffness (Wolpert, Miall, & Kawato, 1998). The forward model makes predictions of the outcomes of motor commands in the form of future and current (real-time) sensory consequences of action (Blakemore, Frith, & Wolpert, 1999; Flanagan & Wing, 1997) and future and current (real-time) arrangements of the motor apparatus (Diedrichsen, Criscimagna-Hemminger, & Shadmehr, 2007; Diedrichsen, Verstynen, Hon, Lehman, & Ivry, 2003; Miall & King, 2008; Wolpert et al., 1998).

Internal models are advantageous for control purposes because they overcome long delays in feedback mechanisms (Kawato, 1999; Miall, Christensen, Cain, & Stanley, 2007; Zago et al., 2008). Internal models use efferent copies of motor commands (copies of outgoing information) developed to achieve a motor state, and afferent sensory information (feedback) on egocentric (one's body), and eccentric ('allocentrc'/'geocentric' - the remaining world) states to make motor and sensory predictions (Blakemore, Wolpert, & Frith, 1998; Vetter & Wolpert, 2000) that allow for feed forward anticipatory adjustments and attenuation of self produced stimulation (Shergill, Bays, Frith, & Wolpert, 2003). A simple illustration of the use of reafferent signals is that if one's eyeball is pushed, the world can appear to move, but if the eye moves voluntarily then the world remains stable. This difference in perception arises because when the eye is pushed there is only movement, whereas when the eye moves voluntarily there is both a movement and a signal that movement will take place (the outgoing motor command).

As the predicted outcome of a motor command is developed by the forward model, anticipatory adjustments are issued by the inverse model to make goal directed motor commands more appropriate (Desmurget & Grafton, 2000; Diedrichsen et al., 2003). These supplementary commands, and changing sensory information regarding the environment and motor apparatus then feed back into the model allowing further predictions and consequentially further anticipatory adjustments (Vetter & Wolpert, 2000). If the actual sensory feedback does not match the predicted feedback then the model can be modified or adapted/developed. Attenuation of sensory feedback occurs when there is a match between model prediction and actual incoming information (Blakemore et al., 1999; Miall et al., 2007) indicating that temporally and spatially accurate predictions of future motor apparatus and states are indeed being made (Bays, Wolpert, & Flanagan, 2005; Blakemore et al., 1999). Further, cerebellar activity has been shown to be associated with error identification and feedforward supplementary motor commands to compensate for such error (Fautrelle, Pichat, Ricolfi, Peyrin, & Bonnetblanc, 2011).

1.2.2 Internal models of objects and relationships

Internal models can also be developed to model the dynamics of the relationship between the body and other objects (Desmurget & Grafton, 2000; Diedrichsen et al., 2003). This is necessary as many tools act as extensions to the upper limbs and so failure to model that relationship would be likely to result in a failure to reach a goal state when using any tool. In such a relationship, the input to the internal model remains largely the same as when predicting body movement alone – visual and haptic information proves input rather than a movement that is generated internally.

There is evidence that it is also possible to model the movement of a free object i.e. an object not under ones direct manipulation (Cerminara, Apps, & Marple-Horvat, 2009; Indovina et al., 2005). The model would store a flexible description of the forces acting on a target and combine this with visual signals to make a prediction of future target position (de Azevedo Neto & Teixeira, 2009; de Rugy, Marinovic, & Wallis, 2011; Hayhoe, Mennie, Sullivan, & Gorgos, 2004). Indeed, the modelling of a free-falling target (i.e. a target falling at *g*) is an idea that is well established in a number of research groups (Lacquaniti & Maioli, 1989a, 1989b; Le Séac'h, Senot, & McIntyre, 2010; Zago et al., 2008). There is experimental evidence that the model yields accurate time to contact estimates for descending targets (McIntyre, Zago, Berthoz, & Lacquaniti, 2001; Vishton, Reardon, & Stevens, 2010; Zago et al., 2004, 2005). Without a predictive model that accounts for acceleration (a second order model involving the second derivative of position) appropriate interception would simply not be possible. Further, ascending targets that are seen to *accelerate* at *g* are actually predicted to *decelerate* as they would in the real-world (Le Séac'h et al., 2010; Senot et al., 2012; Senot, Zago, Lacquaniti, & McIntyre, 2005) indicating the application of a predictive model to trajectories other than descents.

1.2.3 Composition and learning of an internal model of gravity

The break down of an internal model of gravity into forward and inverse components is not simple. One might suggest that the model is purely *forward* because there cannot be control of a free falling object that would necessitate an *inverse* model. The forward model would therefore be derived from visual information only. However, visual information that allows extrapolation of object kinematics can be thought of as constituting the dynamics of movement (an idea similar to Runeson's *kinetics specify dynamics* theory (some dynamic properties of an event can be specified by the kinematics of the event) see Twardy & Bingham (2002)) so movements repeatedly observed with similar accelerations could lead to the assumption of gravitational pull of ~ 9.81 m/s^2 i.e. the dynamics of free fall. This visual information therefore informs the *inverse* model.

There are several alternatives to model acquisition solely from observation. The model may develop from a calculation involving an estimate of impact force at an interception point, the observed (visual and haptic information) mass of the object and a visual estimate of travel time and distance. Several estimates mean the chances of incorrect modelling are higher compared to the simpler method described above, which is a disadvantage, so such a method would likely be avoided if possible by the CNS.

Zago et al. (2005) show that adaptation of an internal model of *g* is event dependent i.e. the model is changed by serial exposure to a stimulus that is different to an original stimulus. It should be noted that while development/modification of internal models tends to be rapid in experimental paradigms such as tool use (Desmurget & Grafton, 2000; Diedrichsen et al., 2003; Imamizu et al., 2000) or force-field adaptation (Flavell, 2008; Hunter, Sacco, Nitsche, & Turner, 2009), these are typically novel situations or situations in which one will have experienced and will continue to experience many varieties of similar events. Whereas, gravity is a constant for which people may never experience any change, and which they will likely experience for their entire lives. Therefore training the gravity model to other values, either in direction or amplitude terms, may be more difficult than training other models, but must nevertheless be possible to allow for variations in objects' kinematics, the environment and CNS functioning. In fact adaptation of the gravity model is resistant to extremely short-term changes in environmental conditions (Chabeauti, Assaiante, & Vaugoyeau, 2012). Though speculations on the conceptual and neurological aspects of learning or adapting internal models have been made (Zago et al., 2005), the main purpose of this thesis is to investigate the directional and amplitude tuning of an already established internal model of gravity, and not to directly investigate by what mechanism(s) it is constructed in the first place.

1.2.4 Ecological theory

The ecological theory posits that observation yields first-order (velocity) time-to-contact information that is sufficient for interceptive actions (such as grasping (Bootsma & Peper, 1992; Savelsbergh, Whiting, & Bootsma, 1991)). Modelling of the aspects of the real world, or higher order versions of time-to-contact, is not necessary because time-to-contact information is continuously updated. As such, the information in the immediate visual scene alone is regarded as sufficient (Baurès, Benguigui, Amorim, & Siegler, 2007) with no, or minimal, processing. This is 'direct perception' of a derivative of an invariant property (i.e. target size) that appears differently to the visual system as the target moves, as oneself moves, or from a combination of the two (e.g. optical expansion signals approach and contraction signals retreat) (Gibson (1979) in Zago, McIntyre, Senot, & Lacquaniti (2009)). The ratio of retinal image size to the rate of change in retinal image size gives continuously updated first order (velocity [first derivative of position]) time to contact estimates (the tau hypothesis).

Arguments against this proposal are, firstly, that this method underestimates the distance travelled by a falling target within only a few hundred milliseconds of the start of the fall (after 200 ms a target will free fall 196.2 mm but it fall roughly the same distance again in only another 83 ms), and secondly, it fails to overcome visuomotor delays when intercepting a target accelerating at *g* (see Zago et al., 2008 for a review) even though first order time-to-contact will converge with the actual contact time as time passes during observation of the visual scene.

1.2.5 Disentangling 'sensory feedback', 'internal models' and 'direct perception'

N.B. In the thesis, use of the term 'direct perception' is simply as a label for the theory (see section 1.2.4). Inclusion of the word 'perception' is not intended as a counter-point to the term 'vision'. Though etymology is not germane, the term 'direct perception' appears to first arise from ecological branch of psychology starting with J. J. Gibson in the 1950s and was not developed by the author of this thesis.

'Sensory feedback' refers the information provided by the sensory systems (such as somatic and visual) along afferent pathways towards the CNS allowing monitoring of the system. Afferent signals result from electro-chemical changes along propagating nerves towards the CNS or PNS. Action planning or reflex will typically follow reception of such a signal. Sensory feedback in a catching scenario, would involve reception of an image of the target on the retina, transmission of information to the CNS and action planned then issued accordingly. Initiation of such action would be around 150-200 ms (an estimate of visuomotor delay (Zago et al., 2008)) after arrival of the target image on the retina meaning that, in a feedback only system, any action towards a dynamic target is out of date – rendering action inapt.

Internal models mitigate reliance on feedback by being feedforward though they do require feedback in order to be updated if predictions are incorrect (see sections 1.2.1 & 1.2.2), and to be 'cued'. For example, the cue for a predictive model describing the unloading of a limb requires an efference copy of a motor command from voluntary action (Diedrichsen et al., 2003). In a catching task the cue would come from the visual system rather than motor system. Any model of gravity would, based on observed current position and velocity of the target, predict future position or time-to-contact using an internalised estimate of *g*.

The use of feedback in the theory of 'direct perception' differs from the use of feedback in the theory of internal models. Whereas internal models can, theoretically, use a 'visual snapshot' of information to predict future free-fall position (using estimated acceleration), in direct perception one continually updates estimates of future position or time-to-contact based on the observed current position and velocity of the target. This leads to first-order predictions of position or time-to-contact that become increasingly more accurate as time-to-contact approaches zero. Feedback would 'feed' this process of estimation.

These three themes (internal models, direct perception and feedback) are not considered exclusive and the existence of one predictive strategy should not wholly rule-out the use of another because the two prediction methods described here (internal models and direct perception) are essentially concepts of a mostly unobservable neural process.

1.3 Internal models and the cerebellum

Classic works (Holmes, 1922 & 1939) highlight the critical role of the cerebellum in motor coordination. More recently, cerebellar lesions have been associated with impairment in learning compensatory muscle activation (Diedrichsen, Verstynen, Lehman, & Ivry, 2005; Flavell, 2008; Lang & Bastian, 1999) which would be possible with a properly functioning internal model. The cerebellum's high plasticity and many efferent and afferent pathways to motor and pre-motor cortices (Kelly & Strick, 2003) suit internal model development in childhood (Schmitz, Martin, & Assaiante, 1999, 2002) and the adjustment as environmental constraints change (Diedrichsen, Verstynen, et al., 2005) that is necessary to allow the model to remain relevant (Bays & Wolpert, 2006; Vetter & Wolpert, 2000; Witney, Goodbody, & Wolpert, 1999; Witney, Vetter, & Wolpert, 2001; Witney & Wolpert, 2003).

Cerebellar activity is associated with movement preparations and internal model recruitment (Bursztyn, Ganesh, Imamizu, Kawato, & Flanagan, 2006), and changes in cerebellar activity with movements that result in self contact (Blakemore, Frith, & Wolpert, 2001; Blakemore et al., 1998) and sensorimotor errors (Fautrelle et al., 2011) indicate a predictive and comparative role for the cerebellum in line with internal model theory. Transcranial magnetic stimulation (TMS) studies (induced transient dysfunction allowing examination of structural processes) support the role of the cerebellum as a predictive state estimator for rapid movements that require the integration of motor efferents and sensory afferents in a predictive capacity (Miall et al., 2007; Miall & King, 2008). Internal models in the cerebellum are also identified in fMRI studies (Fautrelle et al., 2011; Imamizu et al., 2000; Imamizu, Kuroda, Miyauchi, Yoshioka, & Kawato, 2003; Kawato et al., 2003; Luauté et al., 2009) and crucially in single unit recording studies (Angelaki, Shaikh, Green, & Dickman, 2004; Cerminara et al., 2009; Ebner & Pasalar, 2008; Laurens, Meng, & Angelaki, 2013; Pasalar, Roitman, Durfee, & Ebner, 2006; Popa, Hewitt, & Ebner, 2012).

The review by Koziol et al. (2013) discusses the more general use of the cerebellar internal models that, having originally evolved for movement control, now enable and inform more cognitive abilities (as opposed to sensory or motor prediction), for example predicting world events and using tools.

1.4 What is not known

Basic evidence exists for a model of true *g*, but this doesn't take into account an object's density and shape which will affect the way the mass moves through the air. Real world practitioners are able to easily interact with, for example, baseball balls (low air friction, high potential terminal-velocity) and shuttlecocks (high air friction, low terminal-velocity) even when descents are not truly vertical.

No work systematically explores the directional and amplitude tolerance of an internal model of gravity – aspects that determine the model's usefulness in real world situations. A different model may exist for specific situations, or there might be a broadly tuned model that is used across rather different situations. The amplitude and directional tolerances of a gravity model have been examined in simple terms typically by comparing constant velocity with true *g* acceleration, or large deviations from *g*, or by comparing descending targets with ascending or horizontally moving targets. It is important to systematically vary these factors by small amounts to mimic real world interactions more accurately, and to probe the parameters of the model more precisely.

1.5 Differences in the control of eye and arm movements

The world is rich with objects and events that may be relevant to an observer's behaviour. It is the function of the eyes to provide the brain with high quality information about a potentially demanding world. An observer's movement and any number of objects with interesting patterns of movement (constant velocities, accelerations, decelerations, changes in direction etc.) can complicate the visual world.

To fulfil this function, the eyes have special mechanical features that set them apart from other controlled moving body parts. The eyes are low mass, move in a low friction lubricated socket and the muscles that move them have a high percentage (~85%) of fast twitch fibres (Kjellgren, Thornell, Anderson, & Pedrosa-Domellof, (2000) in Levin et al. (2011)) allowing, in principle, very rapid eye movements (up to 500 degrees per second (Oyster, 1999)). The arm by comparison is much more massive so joint rotations require much larger forces and moments of inertia if, for example, the pointing finger on an extended arm were to sweep across the world at the same rate as gaze due to eye movement.

The mechanical advantages when moving the eye are of limited use without a high quality control system to make use of movements. The eyes can therefore move in a number of distinct ways, under the control of a number of neural networks, to cope with the demands of different situations. When the observer is moving, the vestibulo-ocular reflex automatically compensates for self-motion so as to keep the image of the world approximately stationary on the retina (Forrester, Dick, McMenamin, & Roberts, 2008). The optokinetic reflex does the same when the world moves around the observer

(Forrester et al., 2008). So the brain still receives good quality visual information under either or both conditions.

In addition, other control circuits come into play more or less automatically when a particular object in the world becomes important for behaviour. The observer is able to redirect their gaze from wherever else in the world to a new object, or visual 'target' in an approximated single step or 'saccade'. Such eye movements are exceptionally fast (gaze can travel at 500 degrees per second (Oyster, 1999)) and accurate, so that the image of the object is captured very quickly on the fovea (the area of the retina with the highest spatial and temporal resolution and colour sensitivity and where light falls when looking directly at an object (Oyster, 1999)). Once 'captured' the image is kept on the fovea by the smooth pursuit controller which enables the eyes to track the target up to around 50 degrees per second (Forrester et al., 2008) though smooth tracking up to ~100 degrees per second has been reported (Meyer, Lasker, & Robinson, 1985). If the target moves faster than that, pursuit eye movement can fall behind but a 'catch-up' saccade can bring gaze back on target (Oyster, 1999). In this way multiple control systems work in parallel and cooperatively to achieve the desired result of keeping the object of interest under scrutiny.

Given the mechanical and neural control differences that set the eyes apart from the rest of the body so that they can perform their special function, it seems reasonable to expect that there might be differences in the way the eyes track targets falling due to gravity. I therefore analysed and compared eye and arm movements when tracking falling targets so as to identify any such differences.

1.6 Outline of the thesis

From the work discussed, it is clear that there is basic evidence for an internal model of gravity. Though there is not the unreasonable expectation that the model is tuned rigidly to targets descending vertically at *g*, there is yet to be a systematic investigation into the fine tolerances of an internal model of gravity. This thesis presents such a study. Whereas many previous studies have used real or virtual interception (catching, punching or button press) of targets having constant velocity or various accelerations, I used a novel paradigm in which participants were required to track a realistic virtual target moving on a large screen.

A preliminary study was conducted to investigate whether a pre-existing model(s) existed before presenting any moving target that might influence such a model. The study aimed to explore whether apparent object density and direction of motion would affect participants' expectation of movement. To this end, targets could be beach balls, basketballs, or bowling balls that could be imparted with motion vertically (upwards or downwards), horizontally (to the left or to the right) or at 45° diagonally (ascending, descending, left and right). Participants were not instructed about the target or movement condition before each trial. At the start of each trial the participant was presented with two identical targets connected by an arrow indicating the direction of movement. Participants were then asked to imagine the target accelerating at *g* from a start position at the arrow's tail through an end position at the arrow's head and to track that imagined movement. This pilot study is reported in Appendix 7.1 and not as an experimental chapter because of generally poor quality data caused by a series of insurmountable problems at the time of collection (see Appendix 7.3.1). The study proved extremely useful in developing the experimental processes, and in my training using the equipment that was to be used in subsequent experiments. It also highlighted that the hand held laser used by participants needed replacing with one of a more ergonomic design, and that the stimuli presented needed to be more realistic.

In Chapter 2 I describe an experiment exploring directional aspects of an internal forward model of gravity. Participants sat 3 m in front of a large screen onto which a target was projected that accelerated at *g* for 730 ms and moved in straight lines in 15 different directions: ascending vertically, descending vertically, or descending off the vertical at 1-5° [in 1° increments] left and right, 10°, 45°, and 90° right. Participants were required to track the moving target using finger pointing, laser pointing, gaze tracking in isolation, or gaze with either finger pointing or laser pointing. The tracked position was extrapolated onto the screen plane and the error (the difference between instantaneous tracked position and instantaneous target position) was calculated and used a measure of performance.

In Chapter 3 I describe a study of the amplitude aspects of an internal model of gravity. The experimental set-up was as described in Chapter 2. In this experiment the stimuli always descended vertically but accelerated at different percentages of *g*: 50%, 75%, 90%, 95-105% [in 1% increments] and 110% of *g* ($9.81 m/s^2$). Tracking methods and analysis were as described in Chapter 2.

If there is indeed an internal model of *g*, I expected that errors would be smallest when tracking a target moving in the most natural way i.e. errors would be smallest when the target descends vertically as opposed to moving in other directions (Chapter

2), and when the target accelerates at g as opposed to greater, or less than, g (Chapter 3).

In Chapter 4 I describe a study into participants' ability to consciously discriminate between descending targets and targets with some component of horizontal movement. I used the same stimuli as described in Chapter 2 to investigate whether participants' expectation of natural movement would override their experience i.e. would targets that moved very close to naturally be perceived as a natural movement or be perceived correctly.

In Chapter 5 I describe a study similar to that of Chapter 4 but the stimuli match those in Chapter 3 rather than Chapter 2 – participants judged whether a target accelerated at less than g, at g, or greater than g. Again I found no effect of physics expertise, but using the acceleration amplitude varying stimuli I found only weak evidence (in perceptual terms, rather than from tracking performance) in support of an internal model of gravity.

Following the completion of the above experiments, I planned to repeat them using patients with cerebellar lesion or degeneration in order to probe the effects of cerebellar damage on internal model acquisition, maintenance, and performance. This would have revealed how compromised cerebellar contribution to visuomotor control affects performance in relation to naturally, and unnaturally, moving targets. However it became clear that there would be insufficient time to conduct such a study following the incidents detailed in Appendix 7.3.1.

Each individual chapter (2-5) includes full discussion of results. Chapter 6 summarises the main conclusions that are supported by the individual experiments and the entire programme of research.

1.7 References

Angelaki, D. E., Shaikh, A. G., Green, A. M., & Dickman, J. D. (2004). Neurons compute internal models of the physical laws of motion. *Nature*, *430*(July), 560–564.

Baurès, R., Benguigui, N., Amorim, M.-A., & Siegler, I. A. (2007). Intercepting free falling objects: better use Occam's razor than internalize Newton's law. *Vision Research*, *47*(23), 2982–91.

Bays, P. M., & Wolpert, D. M. (2006). Actions and Consequences in Bimanual Interaction Are Represented in Different Coordinate Systems. *Journal of Neurophysiology*, *26*(26), 7121–7126.

Bays, P. M., Wolpert, D. M., & Flanagan, J. R. (2005). Perception of the consequences of self-action is temporally tuned and event driven. *Current Biology*, *15*(12), 1125–8.

Blakemore, S. J., Frith, C. D., & Wolpert, D. M. (1999). Spatio-temporal prediction modulates the perception of self-produced stimuli. *Journal of Cognitive Neuroscience*, *11*(5), 551–9.

Blakemore, S. J., Frith, C. D., & Wolpert, D. M. (2001). The cerebellum is involved in predicting the sensory consequences of action. *Brain Imaging*, *12*(9), 1879–1884.

Blakemore, S. J., Wolpert, D. M., & Frith, C. D. (1998). Central cancellation of self-produced tickle sensation. *Nature Neuroscience*, *1*(7), 635–40.

Bootsma, R., & Peper, C. (1992). Predictive visual information sources for the regulation of action with special emphasis on catching and hitting. In L. Proteau & D. Elliot (Eds.), *Vision and Motor Control* (pp. 285–314). Amsterdam: Amsterdam: North-Holland.

Bursztyn, L. L. C. D., Ganesh, G., Imamizu, H., Kawato, M., & Flanagan, J. R. (2006). Neural Correlates of Internal-Model Loading. *NeuroImage*, *16*, 2440–2445.

Cerminara, N. L., Apps, R., & Marple-Horvat, D. E. (2009). An internal model of a moving visual target in the lateral cerebellum. *Journal of Physiology*, *587*(Pt 2), 429–42.

Chabeauti, P. Y., Assaiante, C., & Vaugoyeau, M. (2012). Extreme short-term environmental constraints do not update internal models of action as assessed from motor imagery in adults. *Neuroscience*, *222*, 69–74.

De Azevedo Neto, R. M., & Teixeira, L. A. (2009). Control of interceptive actions is based on expectancy of time to target arrival. *Experimental Brain Research*, *199*(2), 135–43.

De Rugy, A., Marinovic, W., & Wallis, G. (2011). Neural prediction of complex accelerations for object interception. *Journal of Neurophysiology*, *107*(3), 766–771.

Desmurget, M., & Grafton, S. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences*, *4*(11), 423–431.

Diedrichsen, J., Criscimagna-Hemminger, S., & Shadmehr, R. (2007). Dissociating timing and coordination as functions of the cerebellum. *Journal of Neuroscience*, *27*(23), 6291–6301.

Diedrichsen, J., Verstynen, T., Hon, A., Lehman, S. L., & Ivry, R. B. (2003). Anticipatory adjustments in the unloading task: is an efference copy necessary for learning? *Experimental Brain Research*, *148*(2), 272–6.

Diedrichsen, J., Verstynen, T., Lehman, S. L., & Ivry, R. B. (2005). Cerebellar Involvement in Anticipating the Consequences of Self-Produced Actions During Bimanual Movements. *Journal of Neurophysiology*, *93*(2), 801–812.

Ebner, T. J., & Pasalar, S. (2008). Cerebellum predicts the future motor state. *Cerebellum*, *7*(4), 583–8.

Fautrelle, L., Pichat, C., Ricolfi, F., Peyrin, C., & Bonnetblanc, F. (2011). Catching falling objects: the role of the cerebellum in processing sensory-motor errors that may influence updating of feedforward commands. An fMRI study. *Neuroscience*, *190*, 135–44.

Flanagan, J. R., & Wing, a M. (1997). The role of internal models in motion planning and control: evidence from grip force adjustments during movements of hand-held loads. *Journal of Neuroscience*, *17*(4), 1519–28.

Flavell, J. (2008). *Forcefield adaptation by an internal model in the cerebellum*. Bangor University.

Forrester, J. V., Dick, A. D., McMenamin, P. G., & Roberts, F. (2008). *The Eye*. (Third.). London: Elsevier Ltd.

Gibson, J. J. (1966). *The Senses Considered as Perceptual Systems* (p. 335). London: Allen & Unwin.

Hayhoe, M., Mennie, N., Sullivan, B., & Gorgos, K. (2004). The Role of Internal Models and Prediction in Catching Balls. *Artificial Intelligence*, *4*(8).

Holmes, G. (1922). The Croonian lectures on the the clinical symptoms of cerebellar disease and their interpretation. *Lancet*, *1*, 1231–37.

Holmes, G. (1939). The cerebellum of man. *Brain*, *62*, 1–30.

Hunter, T., Sacco, P., Nitsche, M. A., & Turner, D. L. (2009). Modulation of internal model formation during force field-induced motor learning by anodal transcranial direct current stimulation of primary motor cortex. *The Journal of physiology*, *587*, 2949–2961.

Imamizu, H., Kuroda, T., Miyauchi, S., Yoshioka, T., & Kawato, M. (2003). Modular organization of internal models of tools in the human cerebellum. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(9), 5461–6.

Imamizu, H., Miyauchi, S., Tamada, T., Sasaki, Y., Takino, R., Pütz, B., Kawato, M. (2000). Human cerebellar activity reflecting an acquired internal model of a new tool. *Nature*, *403*(6766), 192–5.

Indovina, I., Maffei, V., Bosco, G., Zago, M., Macaluso, E., & Lacquaniti, F. (2005). Representation of visual gravitational motion in the human vestibular cortex. *Science*, *308*(5720), 416–9.

Kawato, M. (1999). Internal models for motor control and trajectory planning. *Current Opinion in Neurobiology*, *9*(6), 718–727.

Kawato, M., Kuroda, T., Imamizu, H., Nakano, E., Miyauchi, S., & Yoshioka, T. (2003). Internal forward models in the cerebellum: fMRI study on grip force and load force coupling. *Progress in Brain Research*, *142*, 171–88.

Kelly, R. M., & Strick, P. L. (2003). Cerebellar Loops with Motor Cortex and Prefrontal Cortex of a Nonhuman Primate. *Journal of Neuroscience*, *23*(23), 8432– 8444.

Kjellgren, D., Thornell, L. E., Anderson, J., & Pedrosa-Domellof, F. (2000). Myosin heavy chain isoforms in human extraocular muscles. *Investigative Ophthalmology & Visual Science*, *44*, 1419–1425.

Koziol, L. F., Budding, D., Andreasen, N., D'Arrigo, S., Bulgheroni, S., Imamizu, H., … Yamazaki, T. (2013). Consensus Paper: The Cerebellum's Role in Movement and Cognition. *Cerebellum*.

Lacquaniti, F., & Maioli, C. (1989a). The Role of Preparation in Tuning Anticipatory Responses During Catching -. *Journal of Neuroscience*, *9*(January), 134–148.

Lacquaniti, F., & Maioli, C. (1989b). Adaptation to suppression of visual information during catching. *Journal of Neuroscience*, *9*(1), 149–59.

Lang, C. E., & Bastian, A. J. (1999). Cerebellar Subjects Show Impaired Adaptation of Anticipatory EMG During Catching. *Journal of Neurophysiology*, *82*(5), 2108–2119.

Laurens, J., Meng, H., & Angelaki, D. E. (2013). Computation of linear acceleration through an internal model in the macaque cerebellum. *Nature neuroscience*, *16*, 1701–8.

Le Séac'h, A. B., Senot, P., & McIntyre, J. (2010). Egocentric and allocentric reference frames for catching a falling object. *Experimental Brain Research*, *201*(4), 653–62.

Levin, L. A., Nilsson, S. F. E., Ver Hoeve, J., Wu, S. M., Kaufman, P. L., & Alm, A. (Eds.). (2011). *Adler's Physiology of the Eye* (Eleventh.). London: Elsevier Inc.

Luauté, J., Schwartz, S., Rossetti, Y., Spiridon, M., Rode, G., Boisson, D., & Vuilleumier, P. (2009). Dynamic changes in brain activity during prism adaptation. *Journal of Neuroscience*, *29*(1), 169–78.

McIntyre, J., Zago, M., Berthoz, A., & Lacquaniti, F. (2001). Does the brain model Newton's laws? *Nature Neuroscience*, *4*(7), 693–4.

Meyer, C. H., Lasker, A. G., & Robinson, D. A. (1985). The upper limit of human smooth pursuit velocity. *Vision Science*, (4), 561–563.

Miall, R. C., Christensen, L. O. D., Cain, O., & Stanley, J. (2007). Disruption of State Estimation in the Human Lateral Cerebellum. *Cerebellum*, *5*(11), 2733–2744.

Miall, R. C., & King, D. (2008). State Estimation in the Cerebellum. *Cerebellum*, *7*(4), 572–576.

Oyster, C. W. (1999). *The Human Eye: Structure and Function* (First.). Sunderland, Massachusetts: Sinauer Associates, Inc.

Pasalar, S., Roitman, a V, Durfee, W. K., & Ebner, T. J. (2006). Force field effects on cerebellar Purkinje cell discharge with implications for internal models. *Nature Neuroscience*, *9*(11), 1404–11.

Popa, L. S., Hewitt, a. L., & Ebner, T. J. (2012). Predictive and Feedback Performance Errors Are Signaled in the Simple Spike Discharge of Individual Purkinje Cells. *Journal of Neuroscience*, *32*(44), 15345–15358.

Savelsbergh, G. J., Whiting, H. T., & Bootsma, R. J. (1991). Grasping tau. *Journal of Experimental Psychology: Human Perception and Performance*, *17*(2), 315–22.

Schmitz, C., Martin, N., & Assaiante, C. (1999). Development of anticipatory postural adjustments in a bimanual load-lifting task in children. *Experimental Brain Research*, *126*(2), 200–4.

Schmitz, C., Martin, N., & Assaiante, C. (2002). Building anticipatory postural adjustment during childhood: a kinematic and electromyographic analysis of unloading in children from 4 to 8 years of age. *Experimental Brain Research*, *142*(3), 354–64.

Senot, P., Zago, M., Lacquaniti, F., & McIntyre, J. (2005). Anticipating the effects of gravity when intercepting moving objects: differentiating up and down based on nonvisual cues. *Journal of Neurophysiology*, *94*(6), 4471–80.

Senot, P., Zago, M., Le Séac'h, A., Zaoui, M., Berthoz, A., Lacquaniti, F., & McIntyre, J. (2012). When up is down in 0g: how gravity sensing affects the timing of interceptive actions. *Journal of Neuroscience*, *32*(6), 1969–73.

Shepard, R. N. (2001). Perceptual-cognitive universals as reflections of the world. *The Behavioral and brain sciences*, *24*(4), 581–601.

Shergill, S. S., Bays, P. M., Frith, C. D., & Wolpert, D. M. (2003). Two eyes for an eye: the neuroscience of force escalation. *Science*, *301*(5630), 187.

Twardy, C. R., & Bingham, G. P. (2002). Causation, causal perception, and conservation laws. *Perception & psychophysics*, *64*(6), 956–68.

Vetter, P., & Wolpert, D. M. (2000). The CNS updates its context estimate in the absence of feedback. *Neuroreport*, *11*(17), 3783–6.

Vishton, P. M., Reardon, K. M., & Stevens, J. a. (2010). Timing of anticipatory muscle tensing control: responses before and after expected impact. *Experimental Brain Research*, *202*(3), 661–7.

Witney, A. G., Goodbody, S. J., & Wolpert, D. M. (1999). Predictive motor learning of temporal delays. *Journal of Neurophysiology*, *82*(5), 2039–48.

Witney, A. G., Vetter, P., & Wolpert, D. M. (2001). The influence of previous experience on predictive motor control. *Neuroreport*, *12*(4), 649–53.

Witney, A. G., & Wolpert, D. M. (2003). Spatial representation of predictive motor learning. *Journal of Neurophysiology*, *89*(4), 1837–43.

Wolpert, D. M., Miall, R. C., & Kawato, M. (1998). Internal models in the cerebellum. *Trends in Cognitive Sciences*, *2*(9), 338–47.

Zago, M., Bosco, G., Maffei, V., Iosa, M., Ivanenko, Y. P., & Lacquaniti, F. (2004). Internal models of target motion: expected dynamics overrides measured kinematics in timing manual interceptions. *Journal of Neurophysiology*, *91*(4), 1620–34.

Zago, M., Bosco, G., Maffei, V., Iosa, M., Ivanenko, Y. P., & Lacquaniti, F. (2005). Fast Adaptation of the Internal Model of Gravity for Manual Interceptions: Evidence for Event-Dependent Learning. In *Journal of Neurophysiology* (pp. 1055–68).

Zago, M., McIntyre, J., Senot, P., & Lacquaniti, F. (2008). Internal models and prediction of visual gravitational motion. *Vision Research*, *48*(14), 1532–8.

Zago, M., McIntyre, J., Senot, P., & Lacquaniti, F. (2009). Visuo-motor coordination and internal models for object interception. *Experimental Brain Research*, *192*(4), 571–604.

CHAPTER 2
THE DIRECTIONAL ASPECTS OF AN INTERNAL MODEL OF GRAVITY

Studies have shown that interception of free-falling targets occurs with the expectation that the target will accelerate at *g* (9.81 m/s^2) when moving vertically downwards, and the expectation that the target will decelerate when moving vertically upwards. This is commonly taken as evidence for an internal model of gravity, but it also implies that the model is rigidly bound to vertical descents at *g*. In the real world most interceptions of free-falling targets will feature some horizontal component of movement and yet despite this most people are also able to intercept targets in those circumstances. This study is the first to investigate any directional tolerance of an internal model of gravity. Participants executed visually guided tracking of a target accelerating at *g* from stationary and moving in straight lines vertically downwards, vertically upwards, and at a range of angles off vertically downwards. Tracking was either by pointing a finger or a laser, gaze tracking alone or gaze tracking with either finger or laser pointing. In the absence of on-screen accurate feedback of indicated position (i.e. non-laser trials), tracking was found to be typically tuned for vertically descending targets). I suggest that this is evidence that participants used an internal model of gravity to predict the future position of free-falling targets and that ‘direct perception’ was not employed for these tracking tasks. This study also revealed the method by which participants point to distant targets when specificity is required (i.e. ambiguity is possible)

2.1 Introduction

When asked to report the final position of a target moving in a straight line that suddenly vanishes, participants report a position ahead of the true vanishing point (Finke, Freyd, & Shyi, 1986; Finke & Freyd, 1985; Hubbard & Bharucha, 1988; Hubbard, 1990; Nagai, Kazai, & Yagi, 2002), an effect known as 'representational momentum'. Also, participants tend to report the final position of a descending target further ahead than that of an ascending target, and the final position of a horizontally moving target ahead of and below (in the downwards direction) the true final position (Hubbard & Bharucha, 1988; Nagai et al., 2002), an effect known as 'representational gravity'. These findings indicate prediction of the future position of the target based on observed momentum and on an internalisation of real-world effects. In Chapter 1 I discussed evidence in favour of an internal model of gravity that is an internalisation of real world effects. Consequently the model should be directionally tuned, as no person will, for example, ever see a free target ascending at *g*.

There is experimental support for the existence of an internal model of gravity that is directionally tuned. Several studies (Le Séac'h et al., 2010; Senot et al., 2012, 2005) using immersive virtual reality in which participants are required to intercept targets accelerating at *g* that are either ascending or descending towards them, have shown actions are consistent with an expectation of gravity's effect on observed motion i.e. descending targets will accelerate and ascending targets will decelerate. An interception study in space (i.e. zero *g*) revealed that astronauts' actions are tuned with expectation of gravity towards an implied downwards (McIntyre et al., 2001) and even though observing a constant velocity motion, participants will act with an expectation of gravity's effects (Zago et al., 2004).

Though there have been many investigations into the gross up-down differentiation of internal models of gravity (e.g. Le Séac'h et al., 2010; McIntyre et al., 2001; Senot et al., 2012, 2005), there is no study into the fine directional tuning of the model (i.e. small deviations from the vertical). Up-down differentiations are empirically simpler because one does not need to consider more complex parabolic trajectories that would, in natural circumstances arise due to any horizontal component of velocity. The difficulty in an experimental situation involving a horizontal component of velocity is that a perturbation force (the initial impetus for horizontal movement) must be decided upon arbitrarily and result in a particular subset of parabolic trajectories for no particular reason.

A simpler and more incisive experimental design is to have targets accelerating at *g* and moving in straight lines (emulating previous studies) but moving on the vertical or at a range of degrees off the vertical as if gravity were simply acting in these different directions. I employed such stimuli in this study to, amongst other things, identify whether there is a directional deviation threshold beyond which the internal model of gravity might not be utilised. Such trajectories are only possible using virtual stimuli though an immersive virtual environment (as employed by: Le Séac'h et al., 2010; Senot et al., 2012, 2005) was not available to us, so stimuli were designed to be realistic and were projected on a large screen ahead of participants. An interception study with such stimuli is not practical because the target's many potential trajectories must end in the same position (at the participant) meaning that the movement origin has to vary over a large area. For this reason I used a tracking task. This meant that rather than a single prediction of time/space arrival, participants were required to produce a continuous prediction of time/space location throughout the target's travel. This method required just two start positions for the target: a high start position from where targets descended vertically, at degrees off vertical and even horizontally (all at *g*), and a low start position from where targets ascended at *g*. This design allows investigation of the directional tolerance of an internal model of *g* by maintaining the target acceleration at *g,* and straight-line movement, but altering the trajectory angles from the vertical.

In Chapter 1 I briefly discussed the theory of 'direct perception' in relation to prediction of free-falling motion and concluded that this method is less suited to the task than internal modelling. However, it is possible that participants may not employ an internal model and in fact may instead use 'direct perception' i.e. instead of using internalised parameters they may use the information available in the visual scene. The only change in the presented stimulus is the target's direction of motion so discrimination of the method employed to predict target motion should be possible. If 'direct perception' is used, then performance at every condition angle should be similar and not change with practice (though some adaptation may occur as the correct perceptual variable is attuned to), whereas if an internal model of gravity is employed then errors should increase as the angular deviation from vertical increases and errors should be greater for ascending targets than for descending targets. If practice at angle conditions improves tracking performance then it seems likely that an internal predictive model is adapting and thus exists. Adaptation should not be apparent if participants use 'direct perception' because the information available in the visual scene is identical in every condition (apart from changes in the target's direction of motion).

The vast majority of studies into internal modelling of gravity have involved contact with a target whether the target is real and contact physical (Lacquaniti & Maioli, 1989a, 1989b; McIntyre et al., 2001), the target is virtual and contact virtual (Le Séac'h et al., 2010; Senot et al., 2012, 2005) or the target is virtual and the contact real (Zago & Lacquaniti, 2005; Zago et al., 2004, 2005). Temporally and spatially accurate predictions provided by an internal model of one's body are used to judge whether haptic contact is the result of one's actions or an external force (Bays et al., 2005; Blakemore et al., 1999, 1998). Thus, an internal model of external motion may require contact – the assessment of the performance and subsequent adaptation (or lack of adaptation) of prediction of target motion by an internal model may be judged on whether the predicted contact time and space is a good enough match to the experienced contact time and space (or lack of contact). However, participants are able to learn the dynamics of free moving targets and modify learnt dynamics by observation only (Hayhoe et al., 2004). These authors therefore concluded that an internal model predicted the ball's motion. This indicates that our tracking task (which does not involve interception) is suitable for the investigation of any pre-existing internal model of gravity and for adaptation of the internal model following error.

Tracking targets moving in different directions means that the forces required to move one's arm are anisotropic because gravity always pulls downwards. There is evidence of the recruitment of an internal model of gravity's effect on the body in the form of predictions of the sensory consequences and influences on movements (see Topka & Dichgans (1997) for a short review). Also, the gravity force interaction with the arm is modelled during generation of arm trajectories, likely resulting in decreases/increases in muscle torque (rather than joint stiffening) depending on the direction of gravitational field (Gentili, Cahouet, & Papaxanthis, 2007). Thus I do not believe that anisotropic force requirements will affect participants' tracking movements.

Pointing is a trait common to apes and men and develops early in life but the method of pointing can vary widely depending on the intent of the action and the specificity required (see Leavens & Hopkins (1999) for a review). In day-to-day life pointing is not uncommon and an intended target is usually verbally specified (deictic reference) so target acquisition is simple for a second party (Wong & Gutwin, 2010). Pointing is also used in experimental settings for the participant to specify a point in space that the experimenter records. Specificity in these cases is paramount as ambiguity in the indicated location can lead to poor quality or inaccurate data. To reduce ambiguity, pointing in these experiments is often made by contact with a flat surface within arm's reach of the participant (e.g. Neggers & Bekkering, 2001 and Saunders & Knill, 2005). This is a simple way in which people can accurately indicate proximal targets, but when indicating distant targets where specificity is required (i.e. ambiguity is possible) and there is no deictic reference there is, to the authors knowledge, no accepted or identified pointing stratagem. That is, although there has been study of observers' interpretation of an actor's point to specific distant targets (Wong & Gutwin, 2010) the action of the actor's point to specific distant targets has not itself been investigated. This study involves such an investigation and is detailed in Results 2.3.1 and Discussion 2.4.1 of this chapter.

Our aims for this experiment are to:

- Investigate whether there is an internal forward model of gravity.
- Explore its directional tuning/characteristics.
- Investigate whether there is a limitation of what is treated as a natural trajectory.
- Discover the natural method of pointing to distant targets.

Our working hypotheses are:

1. That there is an internal model of gravity.
2. That it is directionally tuned, so that tracking error increases with increasing deviation from vertically downwards movement.
3. Tracking is by looking (with the dominant eye) past the extended index finger of the pointing hand.

2.2 Methods

2.2.1 Participants

Twenty-seven subjects participated in all conditions but several were excluded from each group for behavioural reasons (see Appendix 7.4) leaving 20 participants (13 male, 7 female, mean age ± SD: 28.5 ± 4.9) in the laser condition, 17 participants (10 male, 7 female, mean age ± SD: 28.1 ± 4.9) in the manual condition, 13 participants (7 male, 6 female, mean age ± SD: 30.1 ± 4.1) in the gaze only condition, 10 participants (5 male, 5 female, mean age ± SD: 29.7 ± 4) in the gaze and manual condition, and 11 participants (5 male, 6 female, mean age ± SD: 29.3 ± 4) in the gaze and laser condition. They reported normal or corrected to normal vision (using contact lenses), no neurological or sensorimotor disorders and gave informed consent prior to participation.

Hand dominance was determined using the Edinburgh Handedness Inventory (Oldfield, 1971). The local ethics committee approved experimental procedures.

2.2.2 Determining eye dominance

Eye dominance was determined prior to experimentation using a modified version of the Miles test (Miles, 1930). Participants extended their arms and brought both hands together to leave a small aperture through which they viewed a target 3 m away with both eyes open. Maintaining body position they then alternated which eye was open and reported which eye was open when the target was still visible. That eye was determined to be dominant.

2.2.3 Experimental setup

Participants sat in a darkened room on a 70 cm tall backless stool 3m in front of a vertical projection screen (Sapphire Luxury Fast Fold Projection Screen) (Figure 2-1) illuminated 7 m from the rear using a Canon XEED SX7 (4000 lumens, 1000:1 contrast ratio, 1400x1050 pixels). The projection surface was 3.65x2.75 m and was 29 cm from the floor. A Dell Precision (Intel® Core TM, i72.93 GHz, 4 GB RAM) running QuickTime (V7.6.8) provided projection signals at 60 Hz in 1400x1050 pixels. Projected horizontal level was set with a spirit level.

Left eye in orbit rotations were monitored at 60 Hz using a bright eye ASL Model 501 lightweight eye tracker and Model 6000 control unit with User Interface (V6.24.0.2) run a dedicated PC. Eye position blink filter was set to 1 (no averaging of successive fields) and blink filter set to 12 fields.

A 10-camera Vicon passive marker system and Vicon Nexus (V1.4.115.433000) tracked 16 markers. Six on the dominant hand/arm (finger tip, middle knuckle, base knuckle, above the scaphoid bone, lateral extension of the radius, lateral part of the clavicle), five on the eye tracker (above each eye, 2 posterior and 1 at the apex of the coronal band), two on a laser pen (opposite perpendicular to the cylinder centre) and three on the screen plane (Figure 2-1).

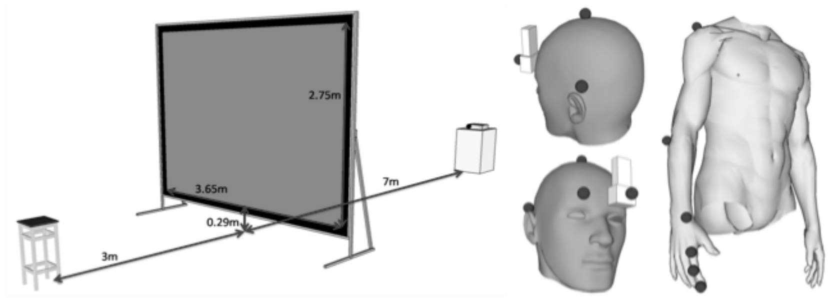


Figure 2-1. Experimental apparatus dimensions and Vicon passive marker locations on the head and the dominant arm/hand.

Marker and eye movements were synchronized and output through a Vicon MX Ultranet (Vicon 612, Oxford Metrics, UK).

2.2.4 Task

Participants were instructed to track a moving target "throughout its appearance and to some way off the edge of the screen" (i.e. maintain 'tracking' after target disappearance) so that movements did not decelerate while the target was still visible. Tracking was either using gaze only or using gaze with either laser pointing or gaze with manual pointing.

Gaze tracking was to fix gaze on the target. Laser tracking constituted aiming a laser pen at the target. The laser was a <1 mW Class IIIa (ANSI Z136.1) push button activated, handheld cylindrical green laser (grasped as a pen to expose its two markers) with a spotlight radius of 7.5 cm at 3 m. Manual tracking constituted extending the index finger of the dominant hand and pointing at the target. Participants were free to move their head and arms but remained seated.

2.2.5 Stimulus videos

In a virtual environment created in Autodesk Maya 2011 an orthogonal camera rendered at 60 Hz a black void occupied by a reflective sphere with a diameter of 15 cm (the target) and an occluding 'mask' 2.475 m below the centre of the target (Figure 2-2). The target descended from a stationary position to behind the 'mask', and accelerated at 9.81 m/s^2. Diffuse illumination moved vertically parallel to the sphere but was behind the camera to avoid implying a vertical through changes in surface illumination. For 1 s the target was red then turned amber for 1 s and then green for the remaining time (Figure 2-3A) with a tone sounding at each colour change. The colour and tonal countdown cues were to allow preparation and reduce movement latency. The target was static for 1 frame (60 Hz) then began to descend at g with position was calculated using Equation 2-1.

Equation 2-1. Calculation for position for a target free falling from stationary

$$d = \frac{1}{2} g \times t^2$$

Where d is distance, g is acceleration (9.81 m/s^2) and t is time.

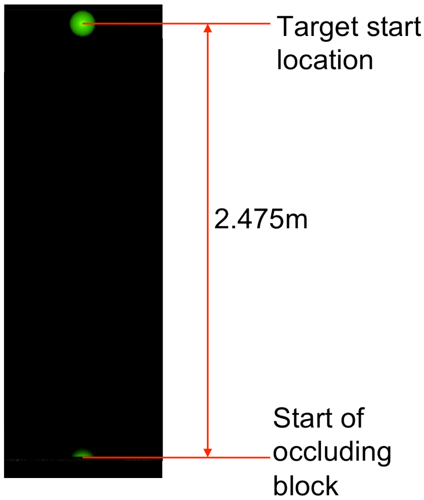


Figure 2-2. Example of the virtual scene rendered in Autodesk Maya 2010. The target is shown at the start position (top) and its final visible position before complete occlusion a 'mask'.

Eyeon Fusion (V5.3, build 78) compiled Maya output to .avi files to which sound was added using Adobe After Effects (V7 Professional). A tone sounded synchronously with target appearance and colour change to cue participants. Thirteen angles off vertically down (1:5° left and right; 10°, 45°, 90° right) were rendered but began at the same location. A target moving vertically upwards began 2.475 m below the descending and horizontally moving targets, and ascended at g.

2.2.6 Protocol

All participants tracked each angle three times using each tracking method. Trials were blocked by a random angle then each tracking method in a random order. Three tracks were performed for each trial giving 135 trials per participant. Being wholly unnatural, the vertically upwards acceleration was always performed last.

One remote trigger began a 20 s marker and gaze recording trial then after a variable delay of 1:3 s a second trigger synchronously began video stimulus playback (15 s) and issued a recorded TTL pulse used later to identify trial events (Figure 2-3B). See Appendix 7.3.2 for details of delay in playback start for confirmation of playback speed.

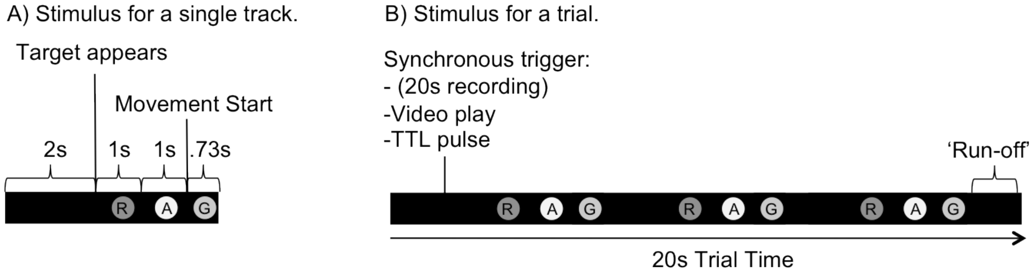


Figure 2-3. A) Time series of a single stimulus: (1/3) of a stimulus video R=Red target, A=Amber target, G=Green target. B) Time series of a full trial of three tracks.

2.2.7 Data processing

Motion capture data. Spline and pattern fills (in Vicon Nexus) were used to fill small gaps typically 5 or fewer consecutive samples in marker tracking. More serious failure to track markers or participants' failure to follow instructions resulted in the exclusion from analysis of 19 of 1215 laser tracks, 104 of 1215 manual tracks (90 of these from two completely removed participants) and 522 of 3105 gaze tracks. Tracking intercepts (indicated position on the screen) for manual pointing and laser pointing were determined using a vector defined by two markers extrapolated to the screen plane.

Gaze tracking data. The eye tracker outputs two voltage signals corresponding to the x and y rotation of the left, tracked, eye in the orbit. Head rotation was summed with these signals to give *x* and *y* gaze angle changes. The gaze vector was extrapolated to give the gaze intercept to a real world plane, the screen, on which the target image was projected. Technical details of these processes are described in Appendix 7.3.3.

2.2.8 Assessing tracking performance

N.B. See the inside back cover for a 'pull-out' describing the errors in terms of direction and sign.

At the end of its trajectory the target fell behind an occluding 'mask' and became invisible (Methods 2.2.5 & Figure 2-2) so participants were only assessed on the period in which at least some part of the target was visible. The distance from the centre of the target to the start of occlusion was 2475 mm, but the target radius was 75 mm meaning that the target was at least partially visible so long as it moved <2550 mm. For the 60 Hz video stimuli, this meant that the moving target was presented for 44 frames (~733 ms) in which it was moving for 43 frames (~716 ms) because the target was stationary in the first frame. Analysis was conducted at 100 Hz, which meant that the number of frames in which the target would be visible is different to that for 60 Hz. At 100 Hz the target would have been presented for 73 frames (730 ms) in which it was moving for 72 frames (720 ms) because the first frame was stationary. The travel distances resulting from the ~3 ms discrepancy arising from conversion from 60 to 100 Hz are minimal (Table 2-1). Thus analysed time frame was 73 samples (730 ms).

Table 2-1. The maximum distance that the target can move and still remain visible for sampling frequencies of 60 Hz and 100 Hz.

a (m/s^2)	Final video frame (60 Hz)	Travel (mm)	Final video frame (100 Hz)	Travel (mm)	Travel difference (mm)
9.81	44	2519.2625	73	2542.7520	-23.489

For analysis purposes, tracking performance was measured perpendicular and parallel to the direction of target motion (Figure 2-4a) (rather than relative to true horizontal and vertical [Figure 2-4b]). To achieve this the tracking intercepts were rotated about the origin of target motion to vertically down i.e. counter-rotated by the condition angle (Figure 2-4c). Vertically upwards trials were rotated 180° around the midpoint of target motion. Following counter-rotation, the sign of the parallel and perpendicular distance from the participant's position to the target's position indicate whether the participant was tracking left or right and above or below the target location (Figure 2-4d and Table 2-2). Tracking error was defined as (tracking - target), consequently when the subject was tracking ahead (below) of or left of the target the in-line (parallel to direction of target movement) and sideways (perpendicular to direction of target movement) errors were negative, and when the subject tracked behind (above) or right of the target the in-line and sideways errors were positive.

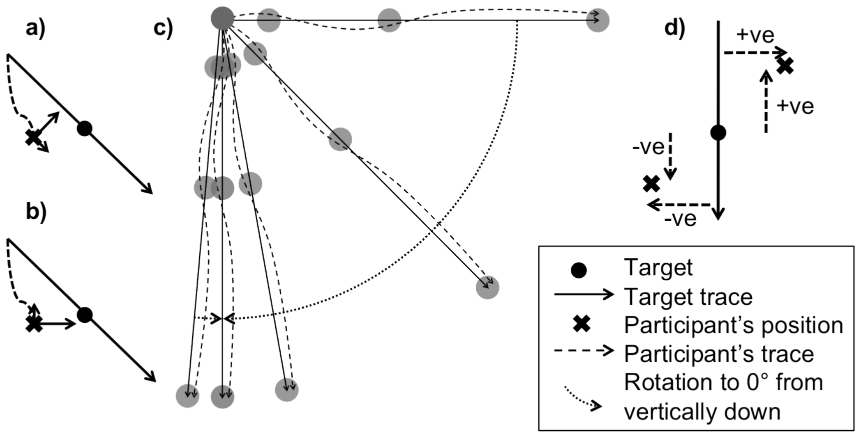


Figure 2-4. Solid lines represent target direction of travel and dashed lines represent tracking intercept. 7a: Error measured perpendicular and parallel to direction of travel. 7b: Error measure relative to true vertical and horizontal. 7c: Target and tracking trajectories rotated to vertically down by the angle of the condition. 7d: Position error signs of participants indicated position relative to target position following counter-rotation by condition angle.

Table 2-2. Meaning of the signs of the errors of indicated position relative to target position following counter-rotation by condition angle.

Error Sign	Horizontal Meaning	Vertical Meaning
Negative	Left of target	Below target (ahead)
Positive	Right of target	Above target (behind)

Velocities and accelerations were derived from position data following counter-rotation by condition angle using a Savitzky-Golay smoothing low-pass filter (Savitzky & Golay, 1964) with 4th order polynomial, 5 Hz frequency cut off). This approach proved effective for removal of high frequency noise without distortion of real tracking signals (Figure 2-5: row 1).

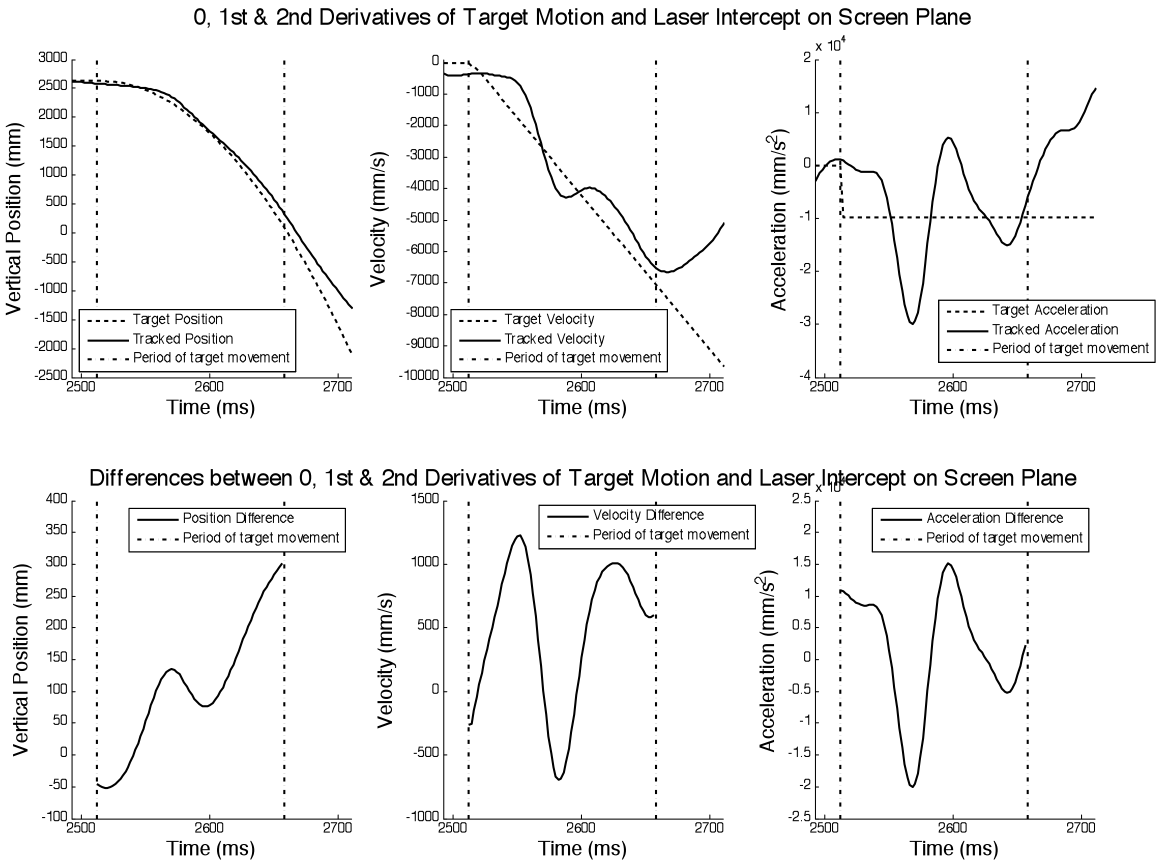


Figure 2-5. An exemplar in-line position time series with derived velocity and acceleration and the difference (error) to target position, velocity and acceleration. Row 1: Target and tracked position with first (velocity) and second (acceleration) derivatives of position. Row 2: The difference between tracking and target motion.

Subtracting the instantaneous target position/velocity/acceleration from instantaneous tracked position/velocity/acceleration gave an error measure that was used to assess performance of the task for the duration of the target's visible movement, a period of 730 ms (Figure 2-5: row 2).

Interpretation of the sideways (perpendicular) velocity and acceleration describes the left-right perpendicular movement of tracking. Interpretation of velocity and acceleration is illustrated in Figure 2-6.

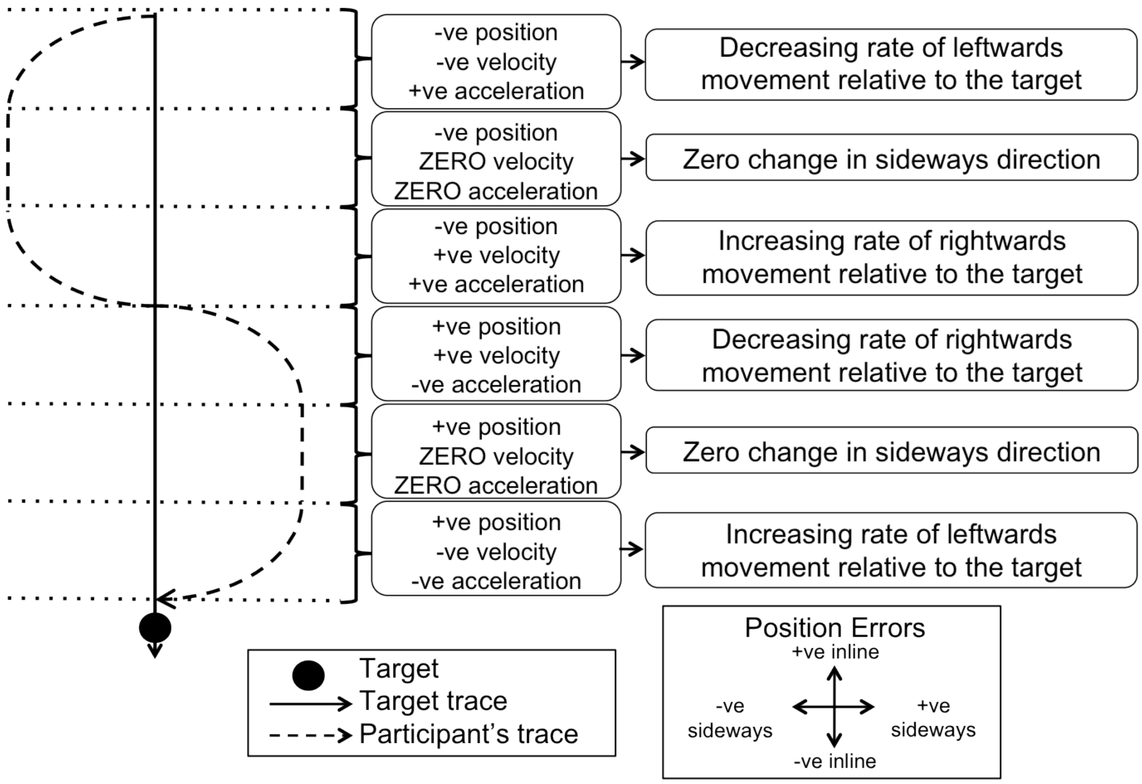


Figure 2-6. Illustration of a tracking trace with interpretation of tracked sideways (perpendicular to direction of target motion) position, velocity and acceleration.

For every instantaneous error a signed (ahead or behind) and unsigned (absolute/modulus i.e. the distance away from the target without specifying direction) value was recorded. The total (summed instantaneous error at each sample from the start to the end of the trial) and the final values (instantaneous error at the sample at the end of the trial) were the measures used in statistical analysis. Error in the direction of target motion (in-line error), and perpendicular to direction of target motion (sideways error) were calculated in this way for position, velocity and acceleration. This resulted in 24 measures for every trial (Figure 2-7).

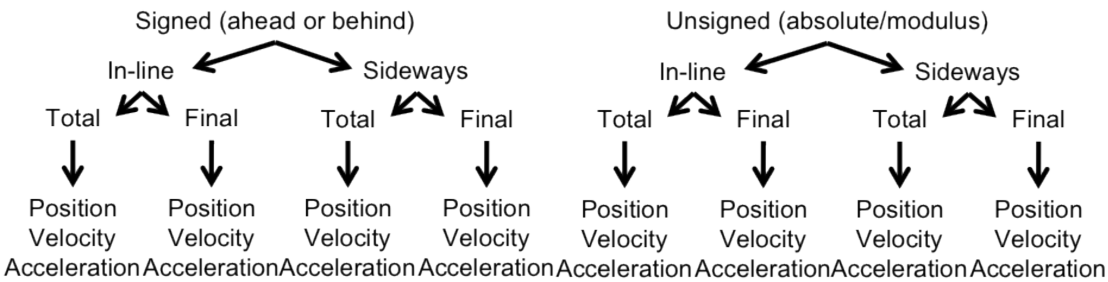


Figure 2-7. Breakdown of measures taken during participants tracking.

2.2.9 Statistical analysis

Due to the extrapolation of the vector defined by a marker pair to an on-screen intercept, any small error in measured marker positions will be amplified over the distance to the screen and will produce visibly anomalous intercepts. The x (horizontal) and z (vertical) components of the 3D tracking intercept were plotted against time for every tracking attempt in all tracking conditions. If following visual inspection they were identified as corrupted they were marked for exclusion from further analysis. Exclusions were because of irrecoverable signal dropout or non-consistent tracking offset indicative of equipment failure. The ability to perform the task (not necessarily clear in raw data) was not a factor in the exclusion decision. See Appendix 7.4 for details of exclusion criteria and rates. This 'cleaned' the data set but resulted in incomplete data matrices for statistical analysis.

The first stage of analysis was a full-factor ANOVA looking for main effects and interactions of target trajectory, method of tracking and tracking repetition number. Method of tracking was then analysed using two-factor (angle and attempt) repeated-measures ANOVAs.

Both these ANOVAs require complete data sets, and handle matrices using listwise deletion (i.e. deletion of a participant when not all values are provided). To minimise data loss, a conservative rule was therefore applied prior to listwise deletion: for subjects who had just a single attempt (value) for an angle missing (e.g. 2nd attempt at 5°) that value was filled with the mean of all values for all other subjects for the same attempt at that angle (i.e. 2nd at 5°) i.e. complete matrices became available for any subject that had only one missing trial at each angle. The number of participants who are included that would otherwise be excluded for each tracking method condition are:

1. Manual condition: 3
2. Laser condition: 1
3. Gaze only condition: 3
4. Gaze in the laser condition: 4
5. Gaze in the manual condition: 5

For details of the replacement rates see Appendix 7.4.

Two-factor repeated-measures ANOVAs were run on all measures (Figure 2-7) for all tracking method conditions. Type IV Sums of Squares were employed to correct for sphericity. Where sphericity was violated (as indicated by Mauchly's Test of

Sphericity) a conservative Greenhouse-Geisser (GG) correction was employed in the interaction effects and where this was non-significant a less conservative Huynh-Feldt (HF) correction is examined. Where sphericity could not be assessed, corrected (Greenhouse-Geisser and Huynh-Feldt) and uncorrected degrees of freedom and significance values are reported. If significance values were mixed (positive and negative) then I state, "… may have been significant… ".

Our working hypothesis was that vertically downwards was the special direction of all those tested in this experiment because an internal model of gravity is thought to be tuned to $9.81m/s^2$ and vertically downwards (see Chapter 1). Therefore, I was particularly interested in comparing results obtained in all other directions to those seen for vertically down. I also expected participants to adapt tracking within each angle condition as they observed their own tracking errors. For these reasons pairwise comparison are not reported (though were conducted) and the effects within each ANOVA were examined using planned comparisons contrasts:

- Simple (first) contrasts for the effect of angle: every angle is compared to the vertically down.

- Repeated contrasts for the effect of attempt: every attempt is compared to its successor i.e. attempt 1 compared to attempt 2 and attempt 2 compared to attempt 3.

For assessing an angle-attempt interaction simple and repeated contrasts are combined: the difference between an attempt and its successor (repeated contrast component) at every angle is compared to the same number attempt and its successor at vertically down (simple contrast component) e.g. the difference from attempt 1 to attempt 2 at 1º left is compared to the difference from attempt 1 to attempt 2 at vertically down error. All effects were considered significant at the 5% level.

2.2.10 Development of analysis

All 24 measures (Figure 2-7) were statistically tested and examined for all 3 tracking conditions: manual/finger pointing; laser pointing; and tracking with eyes/gaze only (Note, the eye movements made under the third condition – gaze only – could only be compared with the eye movements made under the other two conditions – manual and laser – since participants also tracked with their eyes under those two conditions). However, several errors are not reported in this thesis:

- Unsigned (absolute/modulus) errors. From statistical analysis and examination of plots I found that unsigned errors were often less informative and more difficult to interpret than signed errors. In fact, the signed errors were often used to interpret the unsigned errors. See Appendix 7.5.1.
- Final (at 730 ms) errors. There are several reasons for this:
  - For gaze tracking, the end error is approaching the edge of the calibrated region and may be susceptible to technical error.
  - Final errors represent a snapshot of action that is not necessarily representative of overall tracking behaviour that is better characterised by total errors (which for the position measure typically match final error), trajectory and time series plots. See Appendix 7.5.2.
  - By verbal report, many participants believed the virtual target to behave as a real object (Discussion 2.4.10). In particular, one participant reported a persistent expectation that the target would bounce off the floor when 'leaving' the screen edge and so he found it difficult not to decelerate his tracking in preparation for tracking the rising target following bouncing. This represents a potential psychological issue with final error.
- Sideways attempt errors. The roughly equal weighting of left/right (5/8) direction conditions tended to average out interesting features and mask true tracking behaviour.
- In-line acceleration errors. In-line tracking produced acceleration pulses (e.g. Figure 2-12). Consequently, one must be cautious in interpreting total (summed) acceleration error as roughly equal and large amounts of negative and positive error, when summed, would produce a small total error that might be wrongly interpreted.

Though these measures were fully analysed they are therefore not included in this thesis.

2.3 Results

2.3.1 Mode of manual tracking

To capture the most 'natural' method of manual tracking, participants were only instructed to track the target using the extended index finger of their dominant hand. At the study's outset I did not know the way in which pointing would be coordinated, so the locations of Vicon markers (see Methods 2.2.3) were chosen to first identify the tracking method employed by participants, and then to examine the study's main questions.

Simple visual inspection of participants during experimental sessions indicated that all but two participants tracked with an extended arm and index finger and appeared to look past the tip of their index finger. The two who did not, aimed from their hips, which resulted in extremely poor tracking, and these two were excluded from manual tracking analysis.

All valid (see Methods 2.2.9) angles and attempts were included from the manual tracking condition. As described in Methods 2.2.7, tracked position is the intercept of a vector formed by extrapolating the line between two markers onto the screen plane. Because of our observation at the time, the finger tip was chosen as the proximal marker (closest to the screen) to define the pointing vector, and a set of possible other (distal) markers were investigated, located on the shoulder (S), elbow (E), wrist (W), index finger base knuckle (BK), index finger middle knuckle (MK), left eye (LE) and right eye (RE).

It was not possible to place markers at the exact position of each eye, so markers were placed a measured distance above the right and left eyes on the eye tracker head mount. Adjusted versions of the left and right eye position data were calculated (adjusted left eye (ALE) and adjusted right eye (ARE)) using the known vertical distance to estimate true eye position. Eye dominance was also recorded giving a set of four eye dominance-related distal marker descriptions: dominant eye (DE), non-dominant eye (NDE), adjusted dominant eye (ADE) and adjusted non-dominant eye (ANDE). For the different marker pairings using the fingertip and each of the above set of distal markers in turn, the mean and standard deviation of tracking errors was calculated for each attempt at each angle (e.g. 2nd attempt at 5°) across all participants. All the mean values thus calculated (15 directions x 3 attempts = 45 mean values) were then averaged into a global mean value and a global standard deviation. For each tracking method the mean and standard deviation of these means was plotted. In-line and sideways errors were calculated for total, starting (at 1 ms) and final (at 730 ms) measures in signed and absolute terms. Only signed total and starting errors are reported for reasons outlined in Methods 2.2.10.

We hypothesised that the marker pair that consistently produced low mean errors and low standard deviations was the method employed (or a reasonably close approximation) by participants to track targets.

In-line total and starting position errors (Figure 2-8A&B) show that the adjusted dominant eye to fingertip pairings produces the lowest error means and SDs; indeed it is very close to zero for starting error. For both measures the arm and hand to finger pairs produce positive errors (tracking behind the target) consistent with the expectation that those vectors are angled up more steeply than those from the eyes and so produce higher screen intercepts. The adjusted dominant eye to finger tip and adjusted right eye to finger tip produce almost identical errors, as do the adjusted non-dominant eye to fingertip and adjusted left eye to finger tip. This reflects the fact that the right eye was dominant for the majority of subjects (14/17 participants were right dominant) and the left eye non-dominant. Sideways total and starting errors produce a somewhat different pattern (Figure 2-9A&B) but as in the in-line data, adjusted dominant eye yielded lowest errors.

In conclusion, of all the possible sets of distal markers used to generate vectors through the fingertip to the screen, the adjusted dominant eye to fingertip vector produced consistently the lowest errors. I suggest in Discussion that this confirms that participants used the dominant eye to fingertip vector when tracking.

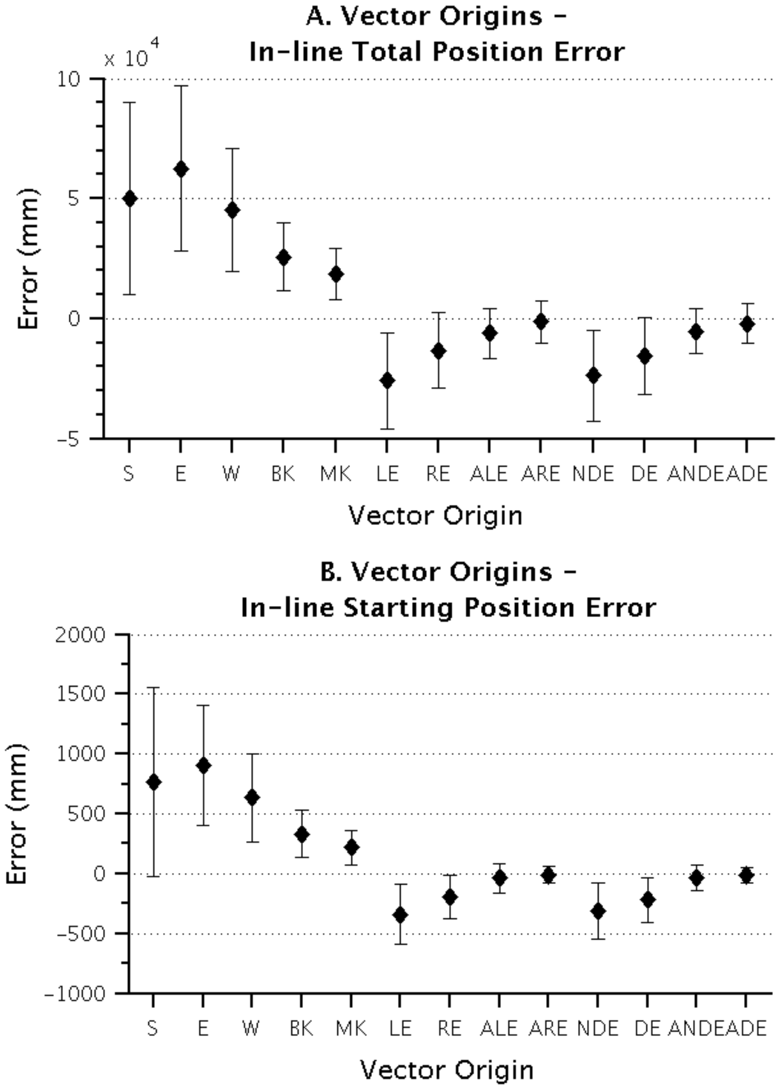


Figure 2-8. Measures of in-line signed total (A) and starting (B) position errors for manual tracking vectors from various origins to the fingertip. Shoulder (S), elbow (E), waist (W), base knuckle (BK), middle knuckle (MK), left eye (LE), right eye (RE), adjusted left eye (ALE), adjusted right eye (ARE), non-dominant eye (NDE), dominant eye (DE), adjusted non-dominant eye (ANDE), adjusted dominant eye (ADE).

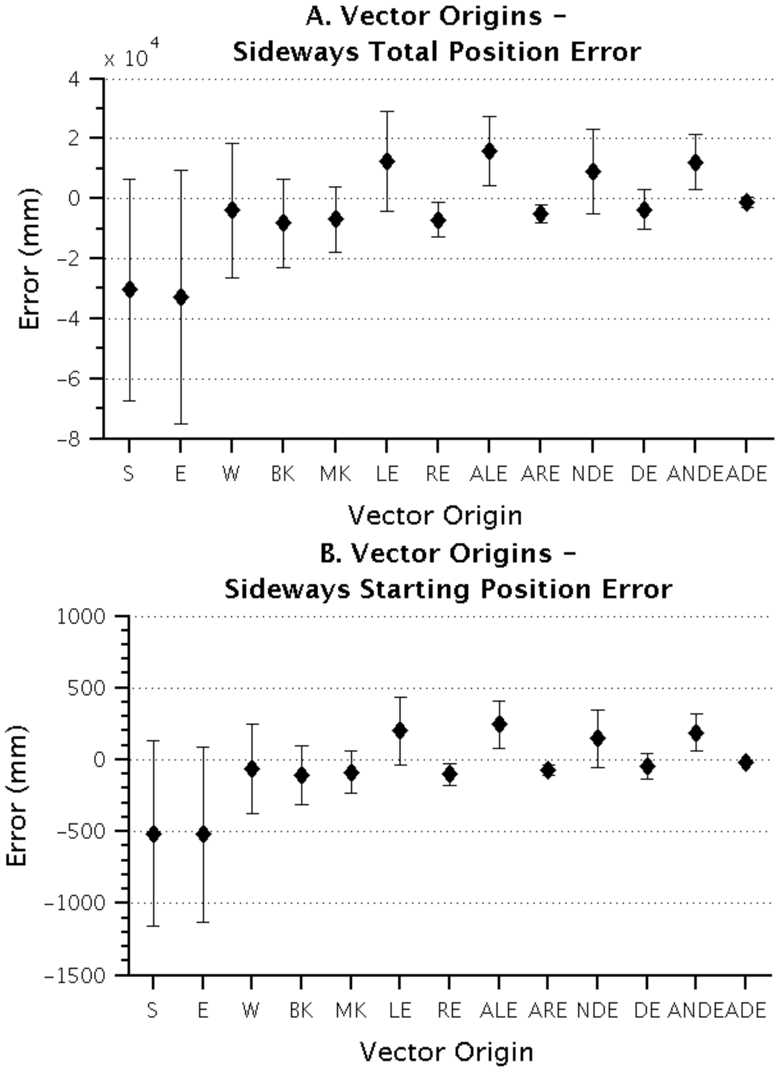


Figure 2-9. Measures of sideways signed total (A) and starting (B) position error for manual tracking vectors from various origins to the finger tip. Shoulder (S), elbow (E), waist (W), base knuckle (BK), middle knuckle (MK), left eye (LE), right eye (RE), adjusted left eye (ALE), adjusted right eye (ARE), non-dominant eye (NDE), dominant eye (DE), adjusted non-dominant eye (ANDE), adjusted dominant eye (ADE)

2.3.2 Main effects on tracking error

The study's main question was the effect of trajectory direction, but it is possible that tracking method or repetition might affect tracking output (total position error). Thus, I first conducted a full-factor, type III SS, univariate ANOVA on these factors. All main effects were significant: trajectory direction ($F(14,3194)=23.282$, $p<.001$), method of tracking ($F(2,3194)=253.176$, $p<.001$), and repetition ($F(2,3194)=124.4$, $p<.001$). The only significant interaction effects were for mode*direction ($F(28,3194)=4.815$, $p<.001$) and mode*repetition ($F(4,3194)=5.789$, $p<.001$) (see Figure 2-10).

Tracking error varied highly significantly depending on target trajectory. A one-way ANOVA was used to examine the differences between tracking errors for each target trajectory. Total position error was significantly affected by direction

(F(14,3180)=18.918, p<.001). Tukey post-hoc tests revealed that tracking error at 90° rightwards and vertically up differed from all other errors (p<.001) but not from one another (Figure 2-10D).

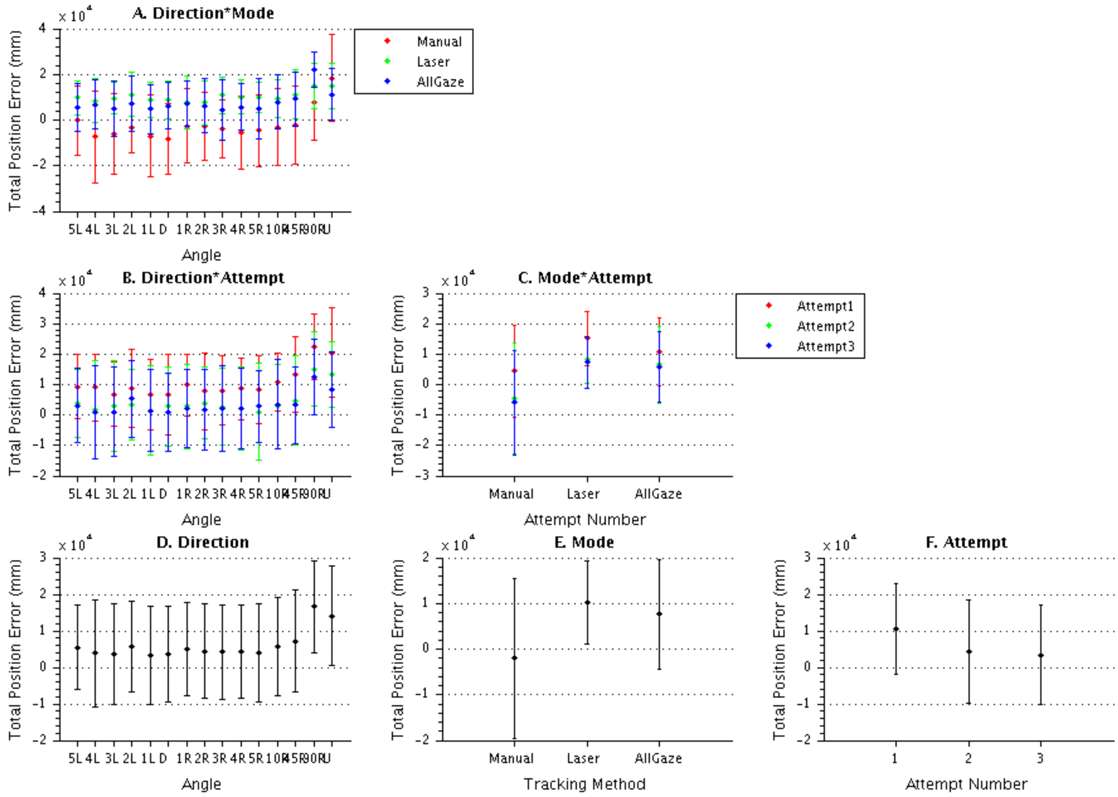


Figure 2-10. Mean and SD of total position error for the main factors of target direction (D), mode of tracing (E) and attempt number (F) with interactions (A,B&C). All tracking angles and attempts are included.

Because tracking method significantly affected tracking error, I used a one-way ANOVA to see where differences lay between the three main tracking conditions: manual tracking (M), laser tracking (L), and all gaze tracking data (GA). I used a second one-way ANOVA to examine differences between the gaze tracking conditions: gaze tracking in isolation (GO), gaze tracking in the manual condition (GM) and gaze tracking in the laser condition (GL). For both ANOVAs a Levene's test revealed a significant (p<.001) violation of homogeneity of variance so Games-Howell post-hoc tests were employed to examine where differences between groups lay. Games-Howell tests are accurate when sample sizes and sample variances are unequal (Field, 2009: pages 374-375).

One-way ANOVA 1: M-L-GA. Total position error was significantly affected by main tracking method (F(2,3192)=210.89, p<.001). Games-Howell post-hoc test revealed all tracking methods differed significantly (p<.001) from one another (Figure 2-10E). **One-way ANOVA 2: GO-GM-GL.** Total position error was significantly affected by gaze tracking methods (F(2,1527)=93.91, p<.001). Games-Howell post-hoc test revealed GO and GM differed significantly from GL ($p<.001$) but not from each other ($p=.99$) (see Figure 2-11B).

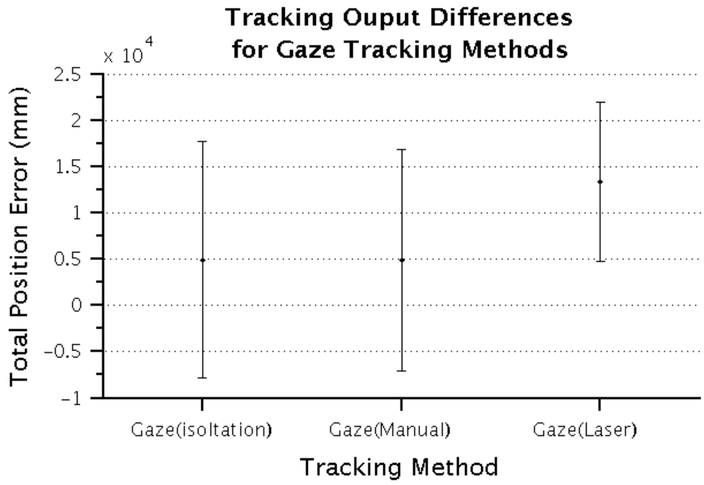


Figure 2-11. Mean and SD of total position error for each gaze tracking in each condition (in isolation, with manual tracking or with laser tracking). All tracking angles and attempts are included.

The three main types of tracking studied (manual tracking, laser tracking and gaze tracking) and the sub-sets of gaze tracking (in isolation and in the manual or laser conditions) were therefore identified as being different from one another. As such, each tracking method was individually examined for the effect of target direction, repetition number and the interaction of these.

2.3.3 Manual tracking

2.3.3.1 Manual tracking along the direction of target movement time series plots

There are several clear features in the in-line tracking component (Figure 2-12):

- Tracking started at approximately zero position error i.e. before the target began to move, tracking was ‘on target’.
- Following a reaction time delay there was a downwards (negative) acceleration pulse which produced a tracking velocity greater than target’s velocity and brought the tracked position from behind (positive error) to ahead of the target.
- Following the acceleration pulse, tracked velocity remained greater than the target’s velocity and tracking was ahead of the target.
- It is possible that there was a second acceleration pulse beginning near the end of the time frame analysed.

There were differences in tracking between first, second and third attempts:

- In the first attempt there was a positive peak in position error (tracking furthest above the target) at approximately 300 ms, but in the second attempt the peak was lower and approximately 75 ms earlier. By the final attempt the peak was lower and earlier still. Following the peak, position error became negative. This error profile represents falling behind the target and then moving ahead of it.

- The tracked position at any time for the second or third attempt is typically below that of the preceding attempt. Tracking fell behind the target and then moved ahead of the target at each attempt, but the distance fallen behind decreased and the distance tracked ahead increased with practice.

- The acceleration plots show what appears to be a second movement occurring slightly earlier with practice.

These changes with repetition mean that the tracked velocity and acceleration profiles match more the target's velocity and acceleration, though the position error does increase as a consequence; tracking was further ahead of the target each time.

Concerning the tracking component perpendicular to the direction of target motion, it is not meaningful to generate plots equivalent to Figure 2-12 because there would be an unequal weighting of left and right target directions (5 left vs. 8 right) brought together. Sideways errors are best considered in data obtained from individual angles (see Results 2.3.3.7 & 2.3.3.8).

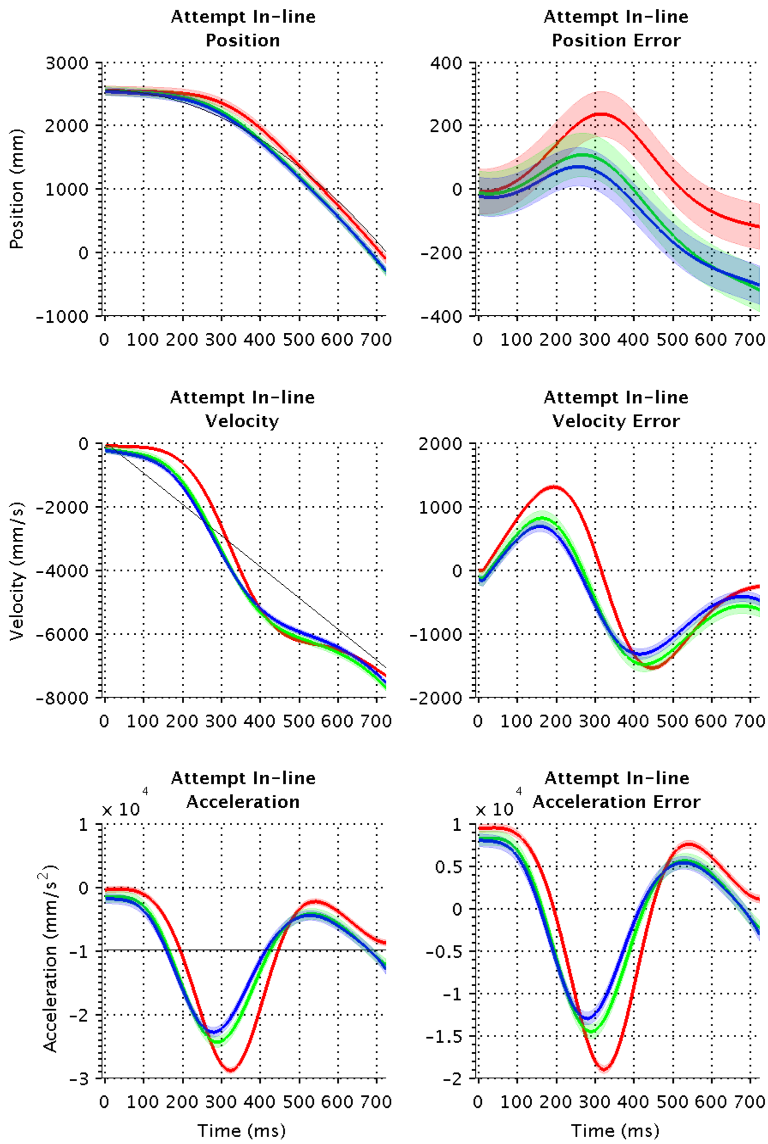


Figure 2-12. Time series of manual tracked in-line position, velocity and acceleration for each attempt. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

2.3.3.2 Manual tracking: Trajectory plots

The thin lines connecting tracked position (thick red, green and blue lines) to the target position (thin black line) are at every odd sample number and indicate whether the tracked position was ahead of or behind the target.

As seen in time series plots (Figure 2-12), following an initial reaction time when tracked position fell behind the target, tracking caught up and moved ahead of the target, before moving too much to the side that the target was moving to. Sideways movement (tracking perpendicular to the direction of target travel) when tracking vertically moving targets (ascending or descending) was small, but the magnitude of sideways movement increased as the target's angular deviation from vertical increased. Tracking a target moving at 45° clearly began in a vertical direction but less so with practice. A small initial vertical tracking movement was seen when the target moved horizontally (rightward), again most clearly at attempt one. I argue in Discussion 2.4.5.1 that this initial downwards tracking deviation shows an expectation that free-falling targets would descend, and that even with practice and online evidence to the contrary this expectation was maintained. See Figure 2-13.

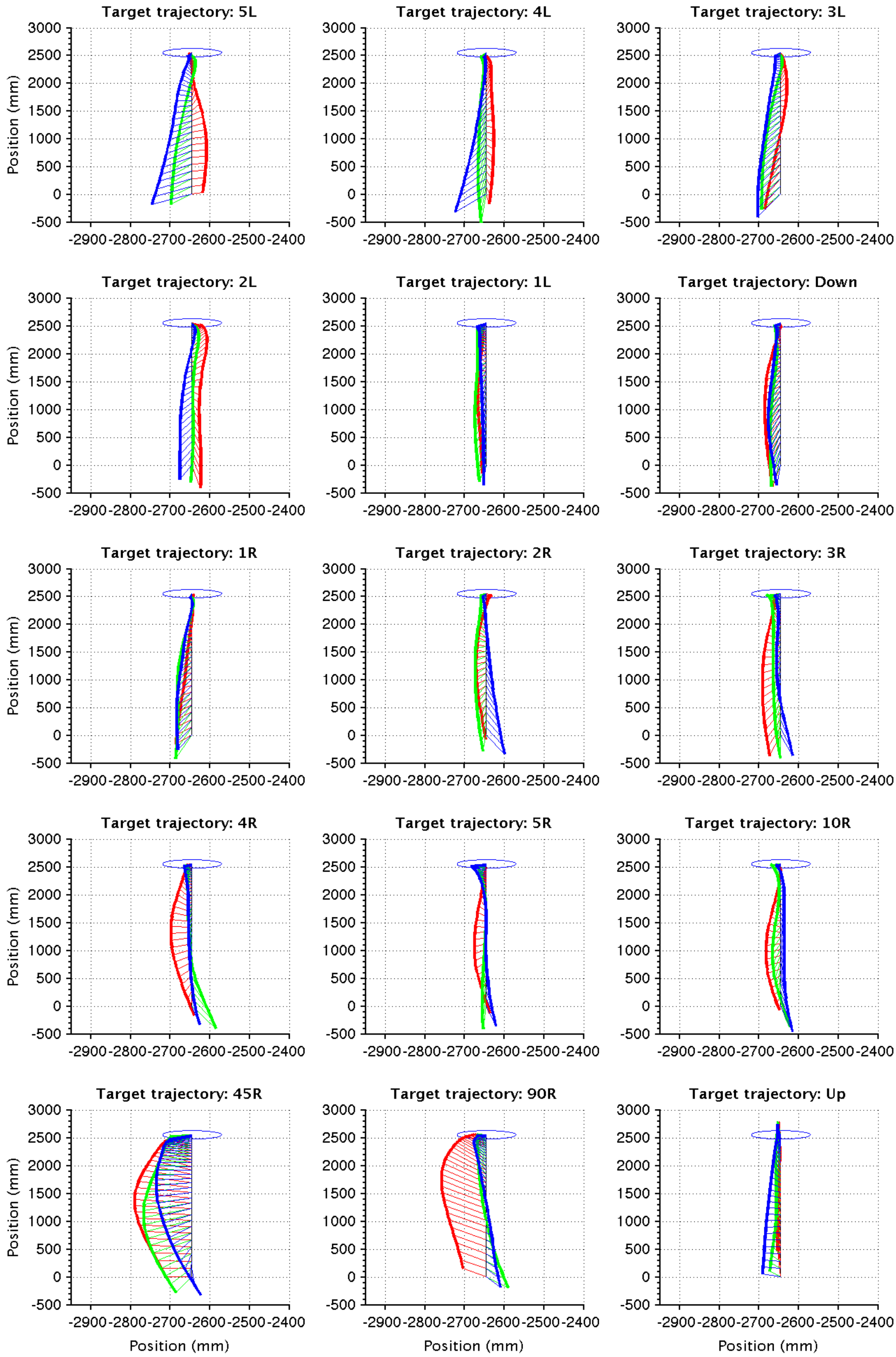


Figure 2-13. Trajectory plots of manual tracking in each angle condition. Thick red, green and blue lines are the mean first, second and third tracking attempts and the thin black is the target's trajectory. Lines joining tracked trajectory to target trajectory are indicate position at every odd sample number.

2.3.3.3 Manual tracking: Time series of tracked position error for individual target directions

Along the direction of target movement (in-line)

Several features identified in the pooled plot of Figure 2-12, such as an initial lag followed by a compensatory overshoot are present in the in-line position error plots for each individual angle (Figure 2-14). Though these features are common to tracking at every angle, they are somewhat flattened when tracking targets moving 45º right, 90º right and vertically up.

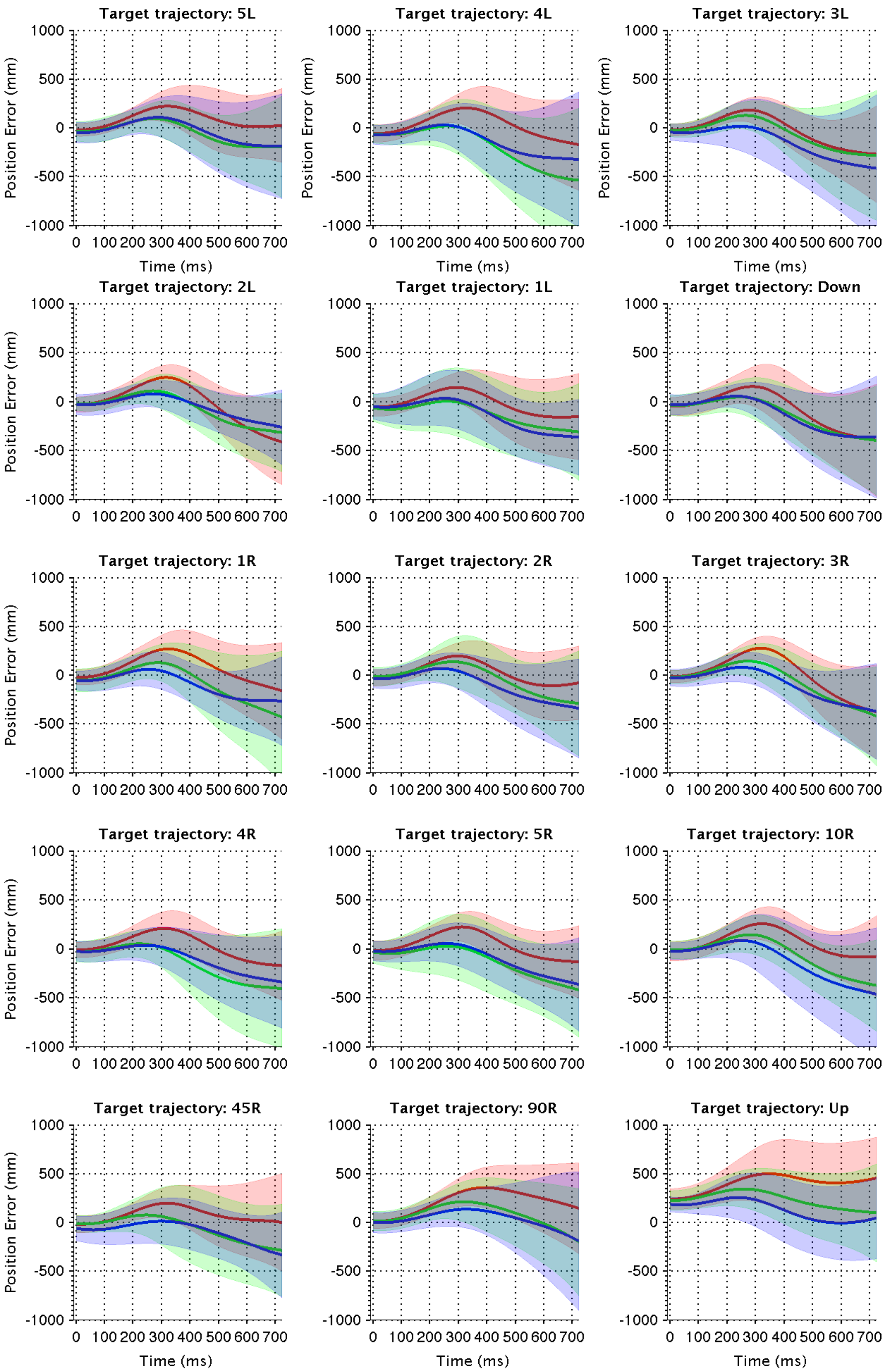


Figure 2-14. Time series of manual tracked in-line position error for each angle condition. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

Perpendicular to the direction of target movement (sideways)

When the target began to move, and the participant remained stationary, an error developed due to the horizontal component of target movement. Subsequently, the participant tracked so as to reduce this developing sideways error and sometimes tracking location deviated further from the vertical than the target (e.g. Figure 2-15 tracking at 2-5^{o} left).

In Results 2.3.3.7 I indentify that for the smallest tested angular deviation from the vertical (1^{o} left or right), tracking was towards the vertical. Sideways errors when tracking at 1^{o} indicated tracking (the intercept on the screen of a vector from the dominant eye to the finger tip) was in the direction of the vertical whereas for larger angles tracking was in the direction target trajectory. In this time series (Figure 2-15) there is a positive gradient to error at 1^{o} left and a negative gradient to error at 1^{o} right whereas the error gradient at >^{o}1 left or right is opposite to that at 1^{o}.

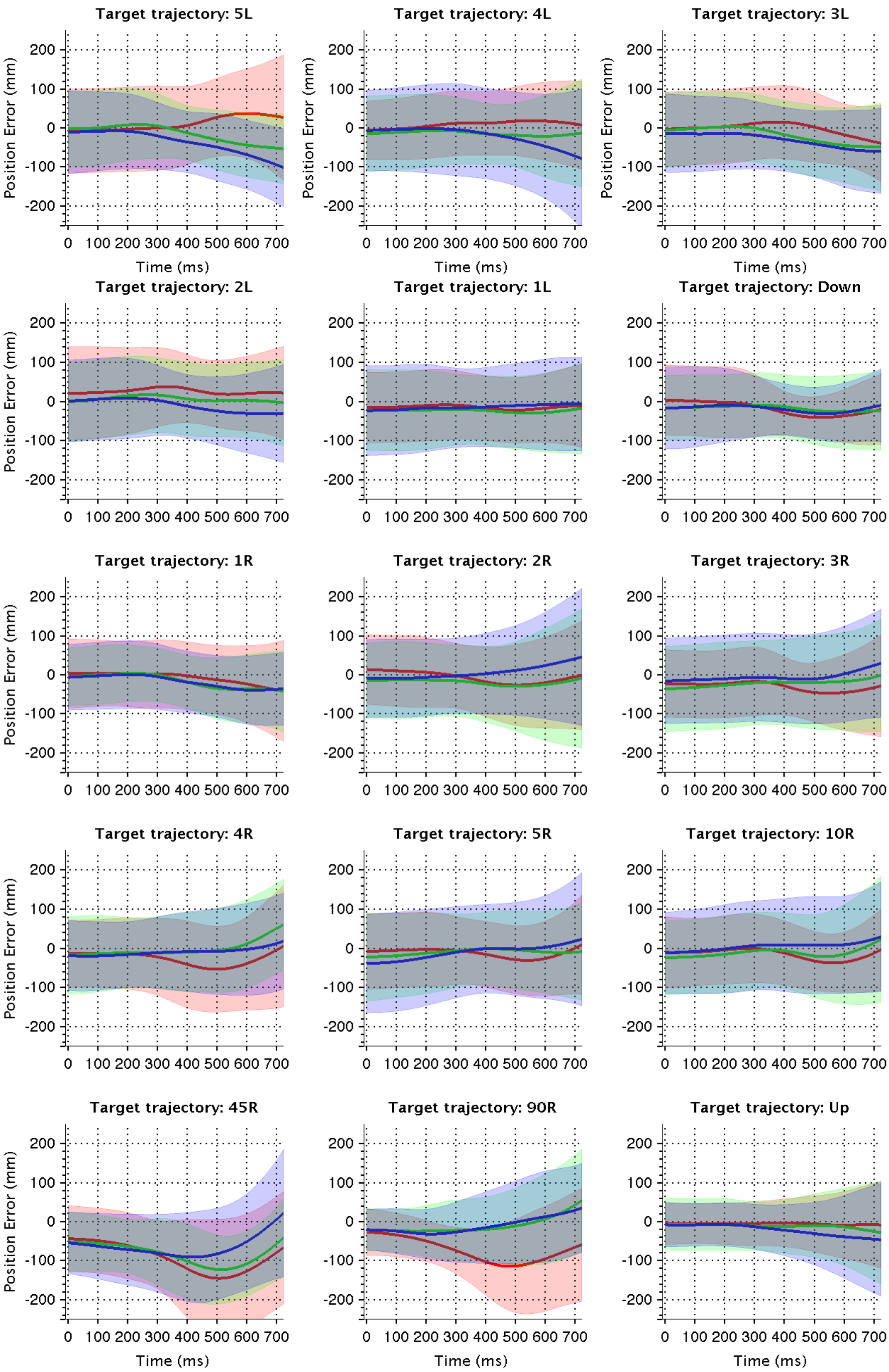


Figure 2-15. Time series of manual tracked sideways position error for each angle condition. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

2.3.3.4 Manual tracking: The effect of target angle on the in-line component of tracking

Total position error was significantly affected by the target path angle (GG $F(6.155,98.476)=12.193$, $p<.001$). Contrasts revealed significant differences from vertically down to 1° right ($F(1,16)=7.725$, $p=.013$); 2° left ($F(1,16)=5.585$, $p=.031$); 2° right ($F(1,16)=5.569$, $p=.031$); 5° left error ($F(1,16)=11.564$, $p=.004$); 10° right ($F(1,16)=6.359$, $p=.023$); 45° right ($F(1,16)=6.332$, $p=.023$); 90° right ($F(1,16)=36.436$, $p<.001$); and vertically up ($F(1,16)=41.484$, $p<.001$).

For tracking a target moving in a direction that included a downwards component, total in-line errors were on the whole negative, meaning participants were overall tracking ahead of the target (Figure 2-16). As the angle away from vertically down increased, the tracking error trended increasingly positively i.e. tracking behind, seen for 90° right and more for vertically up.

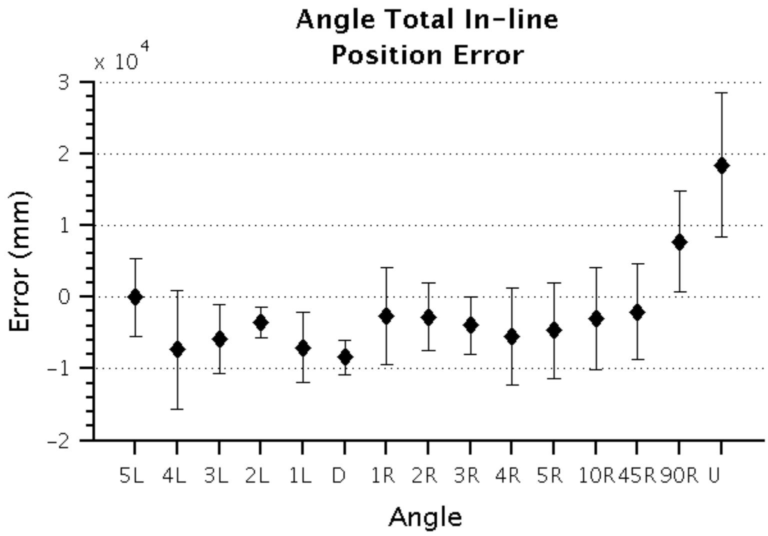


Figure 2-16. Manual tracking mean total position errors (with SD) along the line of target motion for different directions (angles).

Total velocity error was also significantly affected by target direction ($F(14,224)=2.597$, $p=.002$). Contrasts revealed significant differences from vertically down to: 5° left ($F(1,16)=8.893$, $p=.009$); 90° right ($F(1,16)=6.268$, $p=.023$); and vertically up ($F(1,16)=7.794$, $p=.014$).

Tracking was always faster than the target though as angles away from zero increased past 45° the tracking speed more closely matched the target's (Figure 2-17).

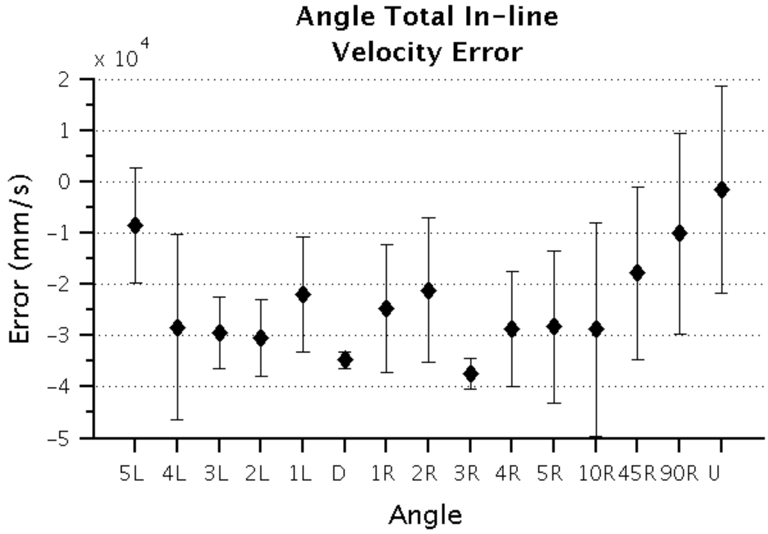


Figure 2-17. Manual tracking mean total velocity errors (with SD) along the line of target motion for different directions (angles).

Section Summary

The overall pattern of results examining the effect on the in-line component of tracking of the target angle (on the vertical and at different directions away from the vertical) indicates that tracking, the output of the manual tracking controller, was on the whole tuned to stay ahead of the target in terms of position and that to achieve this lead the velocity and acceleration of tracking were required to be greater than the target's, bearing in mind the inevitable initial lag in tracking when the target began to move due to visual reaction time. Tracking error when the target accelerated upwards was behind the target. Velocity and acceleration errors confirm tracking was slower than this target.

2.3.3.5 Manual tracking: The effect of repetition (attempt no.) on the in-line component of tracking

Total position ($F(2,32)=29.134$, $p<.001$) and velocity ($F(2,32)=11.174$, $p<.001$) errors were significantly affected by tracking attempt. Contrasts revealed a significant difference from first to second attempt for position ($F(1,16)=36.131$, $p<.001$) and velocity ($F(1,16)=20.742$, $p<.001$).

Position error (Figure 2-18) moved from being typically positive at the first attempt (tracking behind the target) to typically negative (tracking ahead of it) in subsequent attempts and by an amount similar to the lag at the first attempt. However tracking velocity was typically faster than the target (negative) for all attempts and increased in speed significantly from the first to second attempt (Figure 2-18).

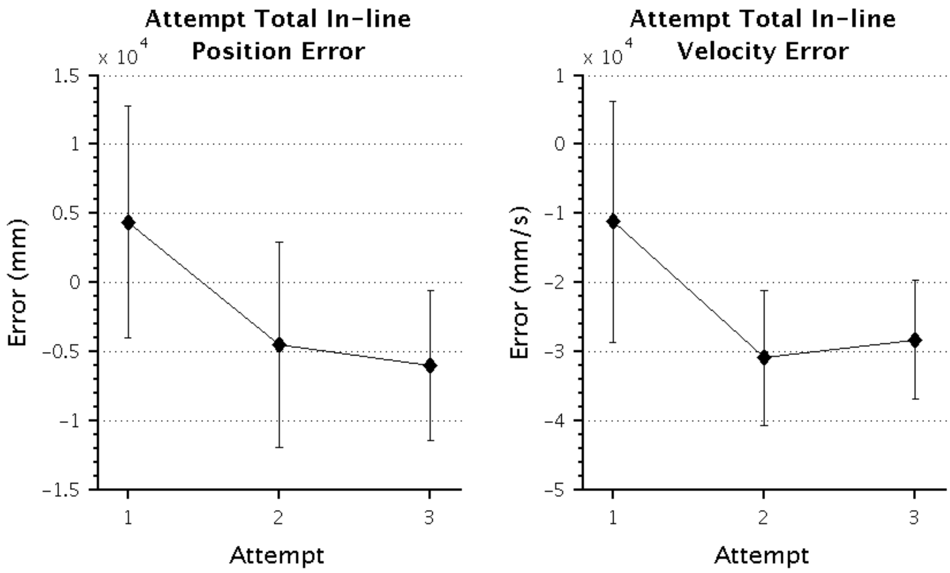


Figure 2-18. Manual tracking mean total position and velocity errors (with SD) along the line of target motion for the effect of repetition (attempt).

Section Summary

The pattern of results examining the effect of repetition, or attempt number, on tracking revealed that errors did not simply decrease with successive attempts, rather they trended, changing with a negative gradient from one attempt to the next. I suggest in Discussion that this is evidence that the goal of manual tracking was to track ahead of the target, which requires tracking to move faster and accelerate faster than the target since they start at the same point, and since the subject experiences an unavoidable reaction time delay.

2.3.3.6 Manual tracking: Angle-attempt interaction on the in-line component of tracking

For total position error results show no significant interaction between the angle condition and the number of the attempts made (uncorrected $F(28,448)=1.206$, $p=.218$; GG $F(7.882,126.106)=1.206$, $p=.301$; HF $F(16.258,126.106)=1.206$, $p=.262$).

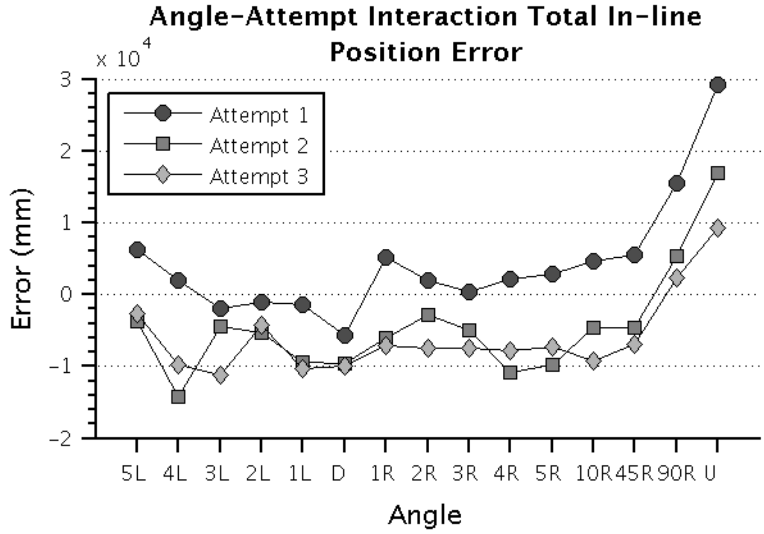


Figure 2-19. Manual tracking mean total position errors along the line of target motion for different directions (angles) and the effect of repetition (attempt).

Section Summary

These data suggest that the goal of tracking ahead of (and faster than) the target implied by the attempt and angle data (Results 2.3.3.5 and 2.3.3.4) was consistent across tracking conditions.

2.3.3.7 Manual tracking: The effect of target angle on the sideways component of tracking

N.B. Tracking trajectories were counter rotated by condition angle to allow comparison of all trajectories to one another. Consequently the target trajectory used for comparison to the tracking trajectories has a zero sideways velocity and acceleration i.e. only moves vertically downwards. See Methods 2.2.8 or the pullout card at the end of this thesis for an explanation of sideways velocity and accelerations.

Total sideways position error was not significantly affected by the target path angle (GG $F(3.335,53.363)=1.889$, $p=.137$, HF $F(4.319,69.102)=1.889$, $p=.117$). Assuming sphericity, there is a significant difference ($F(14,224)=1.889$, $p=.029$) but the violation of sphericity was extreme ($X^2(2)=236.848$, $p<.001$). Contrasts revealed significant differences from vertically down to 2° left ($F(1,16)=7.338$, $p=.015$) and 45° right ($F(1,16)=9.575$, $p=.007$).

With the exception of 2° left all tracking was to the left of the target (negative error) and tracking at every angle where the trajectory was near vertical (i.e. not 45° or 90° right) was roughly equal (Figure 2-20). The smallest tracking error SD is at vertically down indicating that tracking at this angle was the most consistent across participants.

The SD of error at 90° was approximately twice the size of most other SDs which indicates a great deal of variability in tracked trajectory over all the trials in the three attempts. This may be because of poor tracking at the first attempt where this highly atypical direction (most directions being close to or at the vertical) would likely be unexpected causing downward tracking in real-world coordinates and leftwards tracking following counter-rotation. More correct tracking in the second and third attempts (i.e. less negative error or slightly positive error in those attempts) would follow which would bring the mean error closer to zero and cause a larger SD and indeed this was the case (see Results 2.3.3.8).

The SD of error was not unusually high for tracking a target moving at 45° but the mean was especially low indicating tracking that was leftwards of the target for each attempt (confirmed in interaction data, see Results 2.3.3.8). I suggest in Discussion that tracking moved leftwards because this, rather than an unchanging horizontal component, is natural.

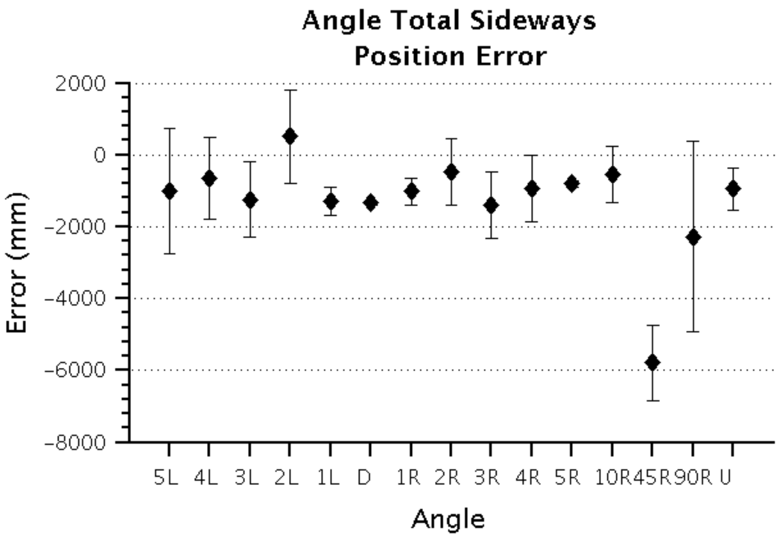


Figure 2-20. Manual tracking mean total position errors (with SD) perpendicular to the line of target motion for different directions (angles).

Total velocity error was significantly affected by target path angle (GG $F(6.131,98.094)=2.493$, $p=.027$). Contrasts revealed significant differences from vertically down to: 3° left ($F(1,16)=8.066$, $p=.012$); 4° right ($F(1,16)=7.704$, $p=.014$); 10° right ($F(1,16)=4.723$, $p=$ 045); 90° right ($F(1,16)=5.327$, $p=.035$).

When tracking a vertically descending or ascending target there is a small negative velocity error (a small movement leftwards) (Figure 2-21). When the target was falling in the direction 1° right of vertical, there was a large negative velocity error i.e. a greater leftwards velocity away from the target and *towards the real-world vertical*. When the target deviated away from vertical in the other direction, 1° left, the resulting velocity error was small but positive, representing a small rightwards velocity away from the target and towards the vertical. Importantly therefore, for the smallest deviation used, 1° either to the left or right of vertical, tracking by the participant was always with a velocity component perpendicular to target motion that meant tracking was away from the target towards the vertical. For all angles greater than 1°, sideways velocity errors showed tracking moving in the direction of the condition angle but greater than was required.

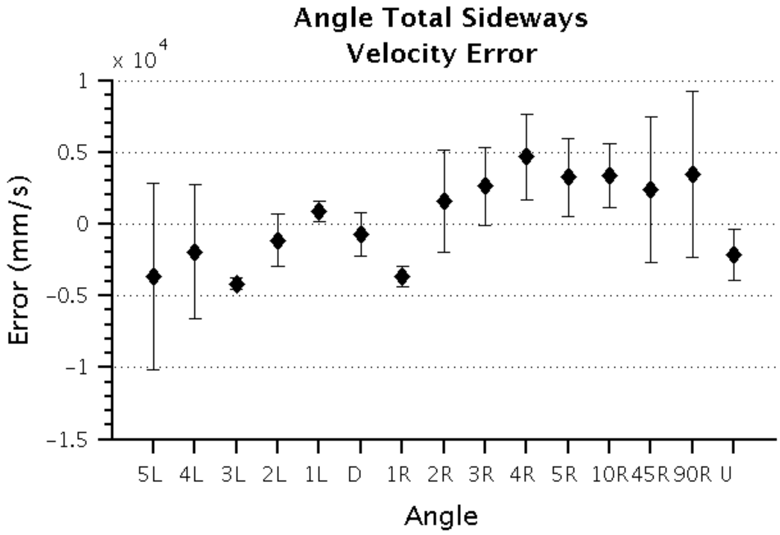


Figure 2-21. Manual tracking mean total velocity errors (with SD) perpendicular to the line of target motion for different directions (angles).

Total acceleration error was significantly affected by the target path angle (F(6.324,101.179)=7.908, p<.001). Contrasts revealed significant differences from vertically down to: 1° right (F(1,16)=5.591, p=.031); 2° left (F(1,16)=5.115, p=.038); 3° left (F(1,16)=4.778, p=.044); 4° left (F(1,16)=5.029, p= 039); 4° right (F(1,16)=6.125, p=.025); 5° left (F(1,16)=12.607, p=.003); 45° right (F(1, 16)=16.458, p=.001). The contrast between vertically down and 10° right approached significance (F(1,16)=4.285, p=.055).

When tracking a target with a leftwards angular deviation from the vertical of >1°, tracking accelerations were negative meaning that tracking was increasing the rate of leftwards movement or decreasing the rate of rightwards movement and the opposite was true for tracking rightwards angles >1° because the error sign was positive (Figure 2-22). The sign of the errors when tracking angles of 1° are the opposite to the sign of error for other angles at the same side as target direction. When considered in relation to the total sideways velocity error, these data indicate that when tracking a target with

>1° of angular deviation from the vertical the tracking motion moves increasingly too much to the same side as the target is moving (i.e. if the target moves left then tracking moves too much left and accelerates leftwards) whereas when tracking a target of 1° angular deviation from the vertical the tracking motion moves increasingly too much in the direction opposite to target movement (i.e. if the target moves left then tracking moves right and accelerates rightwards).

Interestingly there is a clear difference in the tracked sideways accelerations between the two largest angular deviations from the vertical which represent two of the most unnatural sideways trajectories and the most unnatural (90° right) has a lower error than the next most unnatural (45° right). The time series (see Results 2.3.3.1) reveal that tracking adapted to follow the horizontally moving target with practice and thus the large corrective movement in the first attempt was not required or was smaller in subsequent attempts. Little adaptation to target movement occurred when tracking a diagonally moving target so the corrective movement was more or less maintained in all attempts.

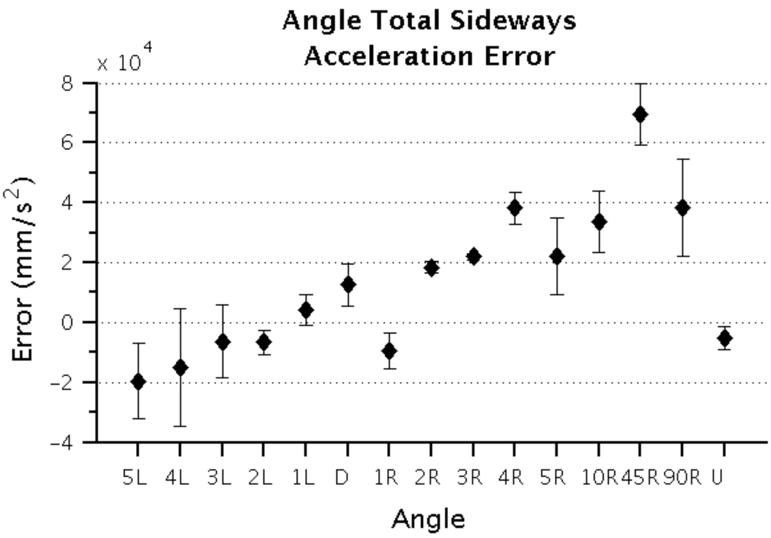


Figure 2-22. Manual tracking mean total acceleration errors (with SD) perpendicular to the line of target motion for different directions (angles).

Section Summary

The most important finding from these angle data is that for the smallest angular deviation used (1° left or right) errors indicate tracking position and movement to be towards to the vertical whereas for larger angles position and movement are in the direction of the target trajectory. In Discussion 2.4.5.2 I suggest that this indicates that for these angles either angular deviation was not noticed or target motion was assumed to be vertically downwards.

We also found that for a target moving at 45° from the vertical tracking was poor in terms of sideways error and that there was little or no improvement with practice because the mean error was large and the SD small. This was not the case for tracking a horizontally moving target where tracking did appear to improve from a poor first attempt.

2.3.3.8 Manual tracking: Angle-attempt interaction on the sideways component of tracking

For total position error the results show that there was a significant interaction between the angle condition and the number of attempts made (uncorrected $F(28,448)=2.776$, $p<.001$; GG $F(8.523,136.368)=2.\ 776$, $p=.006$; HF $F(19.111,305.772)=2.776$, $p<.001$). Contrasts revealed a significant difference between first attempt and second attempt for 90° right ($F(1,16)=5.328$, $p=.035$).

Vertically up and vertically down are tracked roughly equally well and show little change from one attempt to the next though both are tracked to the left (following counter-rotation) of the target (Figure 2-23). For leftwards angles tracking was initially to the right and the distance right increased as the angle increased (with the exception of 2° left) which may indicate an assumption of a vertically descending target on the first attempt (reasonable given no indication of initial movement). Second attempts tended to be leftwards of the target and third attempts further still. The distance to the left (away from the target) increased as angle increased. This was not the case in the equivalent rightwards angles for which participants tracked typically left of the target for all attempts and tended to decrease their distance left from the target by the third attempt.

The position error at 45° right improved over attempts but remained far to the left of the target by the third attempt (an error greater than all others) whereas 90°, which also had a large first attempt error, reduced error to the level of the vertical trajectories for the second and third attempts. I suggest reasons for these differences seen at 45° and 90° (and compared to all other angles) in Discussion.

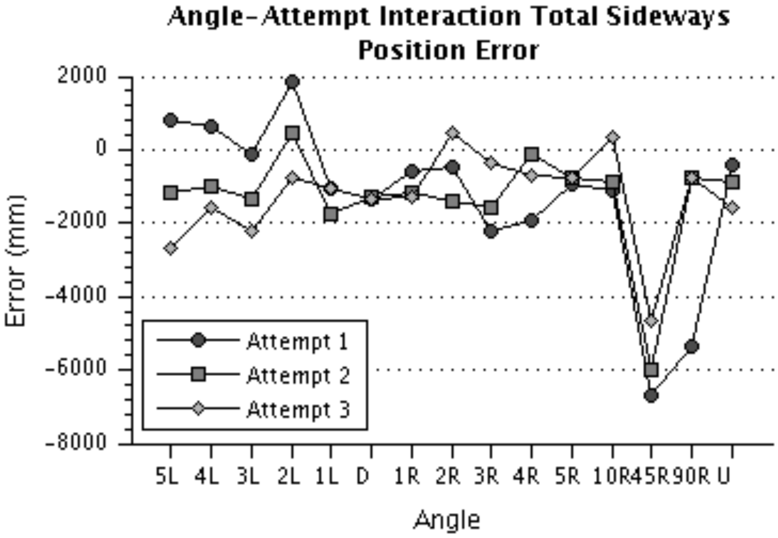


Figure 2-23. Manual tracking mean total position errors perpendicular to the line of target motion for different directions (angles) and the effect of repetition (attempt).

For total velocity error the results show a significant interaction between the angle condition and the number of attempts made (uncorrected $F(28,448)=3.126$, $p<.001$; GG $F(8.638,128.212)=3.126$, $p=.002$; HF $F(19.676,314.817)=3.126$, $p<.001$). Contrasts revealed a significant difference between second attempt and third attempt for 2° left ($F(1,16)=4.719$, $p=.045$); between second attempt and third attempt for 4° left ($F(1,16)=5.836$, $p=.028$); between first attempt and second attempt for 5° left ($F(1,16)=9.929$, $p=.006$); and between first attempt and second attempt for 90° right ($F(1,16)=6.025$, $p=.026$).

Tracking at vertically down went from moving leftwards at the first attempt to moving rightwards by the third attempt and the error reduced over by that attempt (Figure 2-24). When tracking a vertically ascending target the error increased and moved increasingly leftwards over the three attempts. Error changed the least when tracking 1° left or right of vertical and the direction of the error indicated tracking moving towards the vertical. For all other angles the tendency was to track closely the parallel position of the target (near zero error) at the first attempt and then move increasingly to the same side as the target trajectory over the next two attempts. Tracking towards the real-world vertical at with target trajectories of 1° and in the direction of trajectory movement for angles >1° was also found in the sideways angle measures (Results 2.3.3.7).

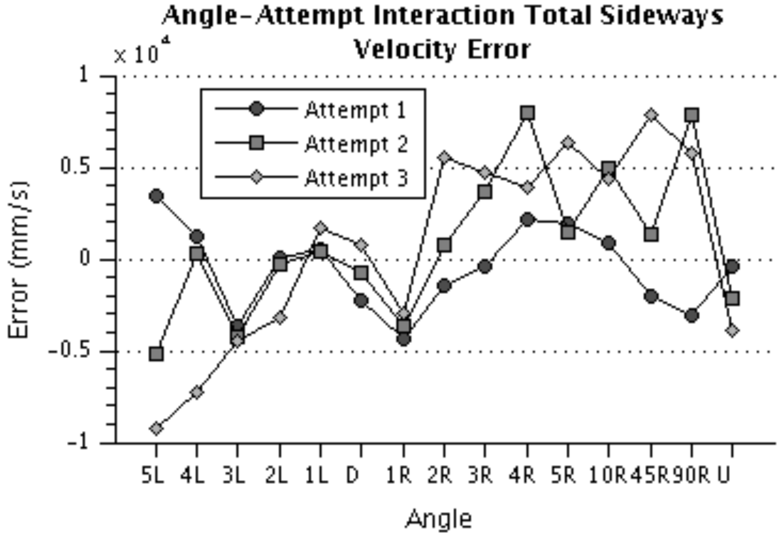


Figure 2-24. Manual tracking mean total velocity errors perpendicular to the line of target motion for different directions (angles) and the effect of repetition (attempt).

Section Summary

The difference between attempt tracking errors for a given angle vary least for vertically moving targets and targets moving at only 1° away from the vertical indicating great consistency, and that participants did not change their tracking control with repetition at these angles.

2.3.4 Laser tracking

2.3.4.1 Laser tracking along the direction of target movement time series plots

These time series (Figure 2-25), especially the in-line velocity and acceleration, indicate that participants produced not an in-line constant acceleration at *g* (i.e. a flat line in acceleration plot at -9810 mm/s^2) as they should have, but rather a single pulse of acceleration peaking at ~275 ms and over by ~550 ms. This resulted in a sigmoid velocity profile starting at zero velocity, with a final velocity of approx. -5000 mm/s. This was maintained to the end of the trial (plateau from ~550 to ~730 ms). The participants' tracking velocity exceeded target velocity in the middle of the movement, in the period 300-500 ms, during which the tracking laser spot was initially closing on the target (catching up) but thereafter increasingly fell behind. Unlike the manual condition there is no sign of a second movement towards the end of the tracking time.

There were reductions in position, velocity and acceleration errors with practice and single tracking attempt appears to reduce tracking error close to what may be the limit as there only a small change following the second tracking attempt.

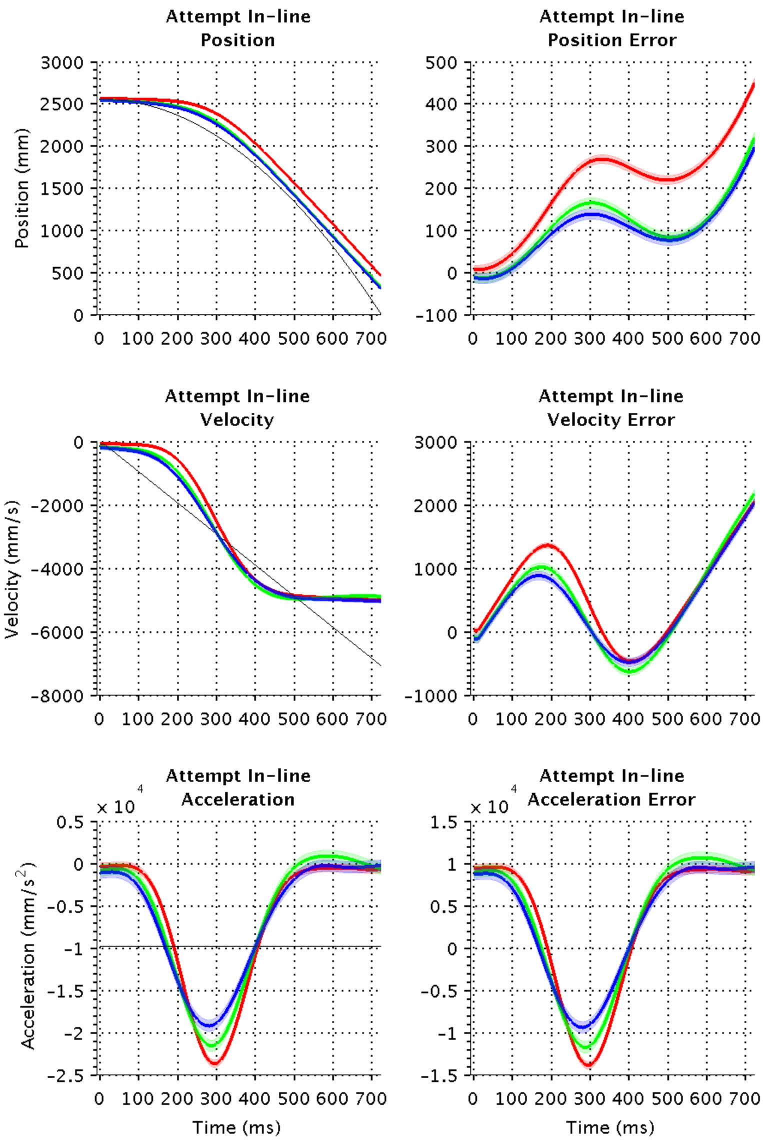


Figure 2-25. Time series of laser tracked in-line position, velocity and acceleration for each attempt. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

2.3.4.2 Laser tracking: Trajectory plots

See Results 2.3.3.2 for a description the plot components.

Tracking appears to be behind the target in all angle conditions (Figure 2-26) as was found in the in-line time series (Figure 2-25). Sideways errors when tracking at trajectories <10° are small but show a small movement in the direction of target motion towards the end of the tracking period and this deviation tends to increase as the condition angle increases. First attempt track at when the target moves at 45° or 90° from the vertical, show tracking moving towards vertically down before correcting towards the actual target movement. This may indicate that participants expected a descending target but were able to correct developing error using the laser feedback. At the second and third tracking attempts for these angles there is no downwards deflection but there is an upward deflection towards the end of the tracking movement that is reminiscent of the sideways movements at smaller angles.

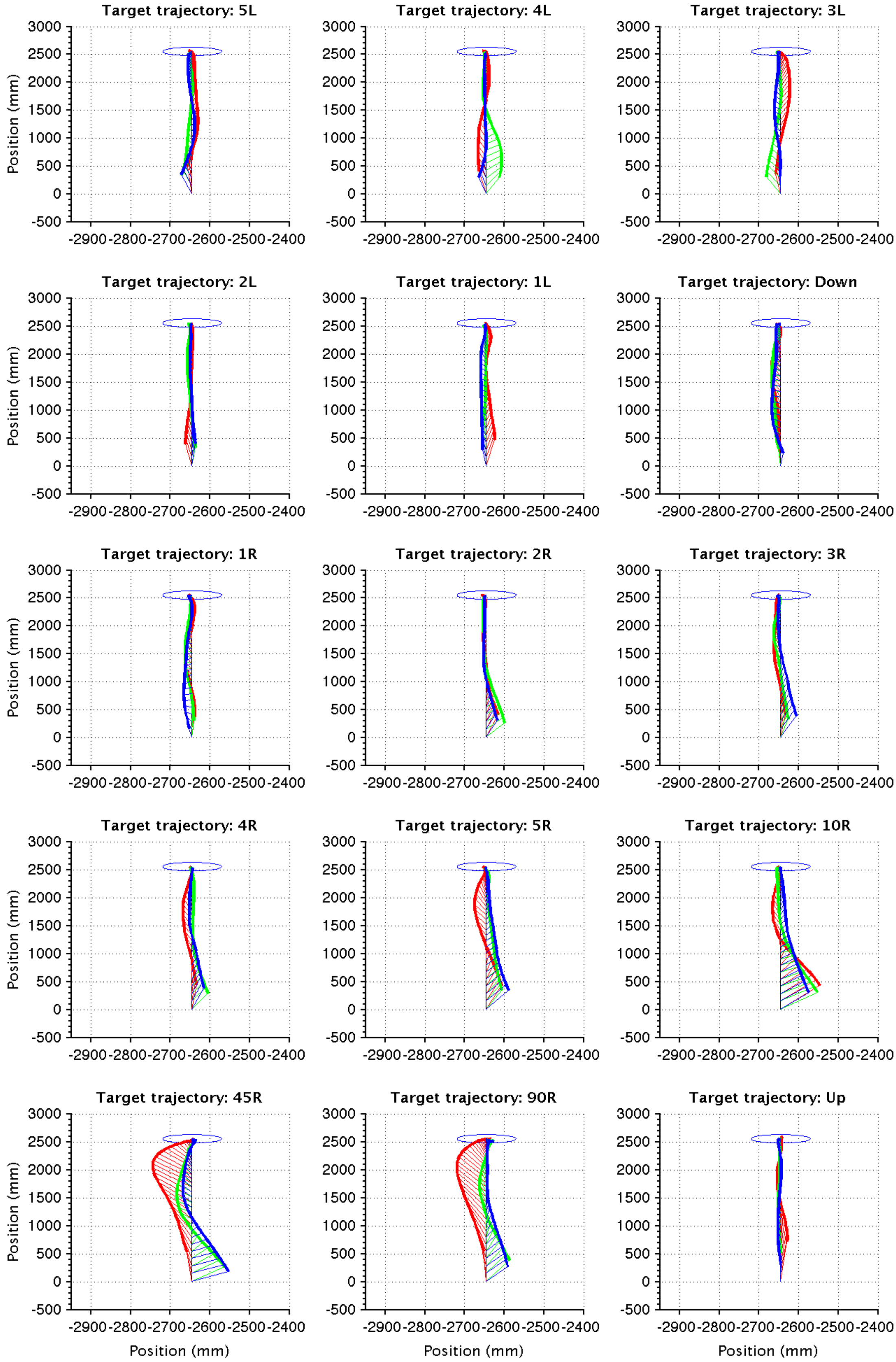


Figure 2-26. Trajectory plots of laser tracking in each angle condition. Thick red, green and blue lines are the mean first, second and third tracking attempts and the thin black is the target's trajectory. Lines joining tracked trajectory to target trajectory are indicate position at every odd sample number.

2.3.4.3 Laser tracking: Time series of tracked position error for individual target directions

Along the direction of target movement (in-line)

The time of the first movement at each attempt for all angles is broadly similar (~300 ms) (Figure 2-27) and is identical to the movement time identified in the time series of position, velocity and acceleration (Figure 2-25). This is a similar finding to that in manual tracking but unlike the manual condition the time of this first movement does not decrease with practice (attempts two and three). Also, in the manual condition position error continues on a negative gradient following the first movement whereas here the movement resulted in a reduction in position error but an insufficient increase in velocity (see Figure 2-25) caused the position error to increase towards the end of movement. The greater velocity in the manual condition (Figure 2-12) brought tracking ahead of, or further ahead of, the target following the first movement at ~300 ms which was typically behind the target.

Tracking in the laser condition was almost always behind the target and varied little between angular deviations from the vertical of <45º (Figure 2-27). First attempt errors when tracking targets moving 45º or 90º right were generally larger and increased more linearly than at other angles though second and third attempt error profiles were similar to profiles at other angles.

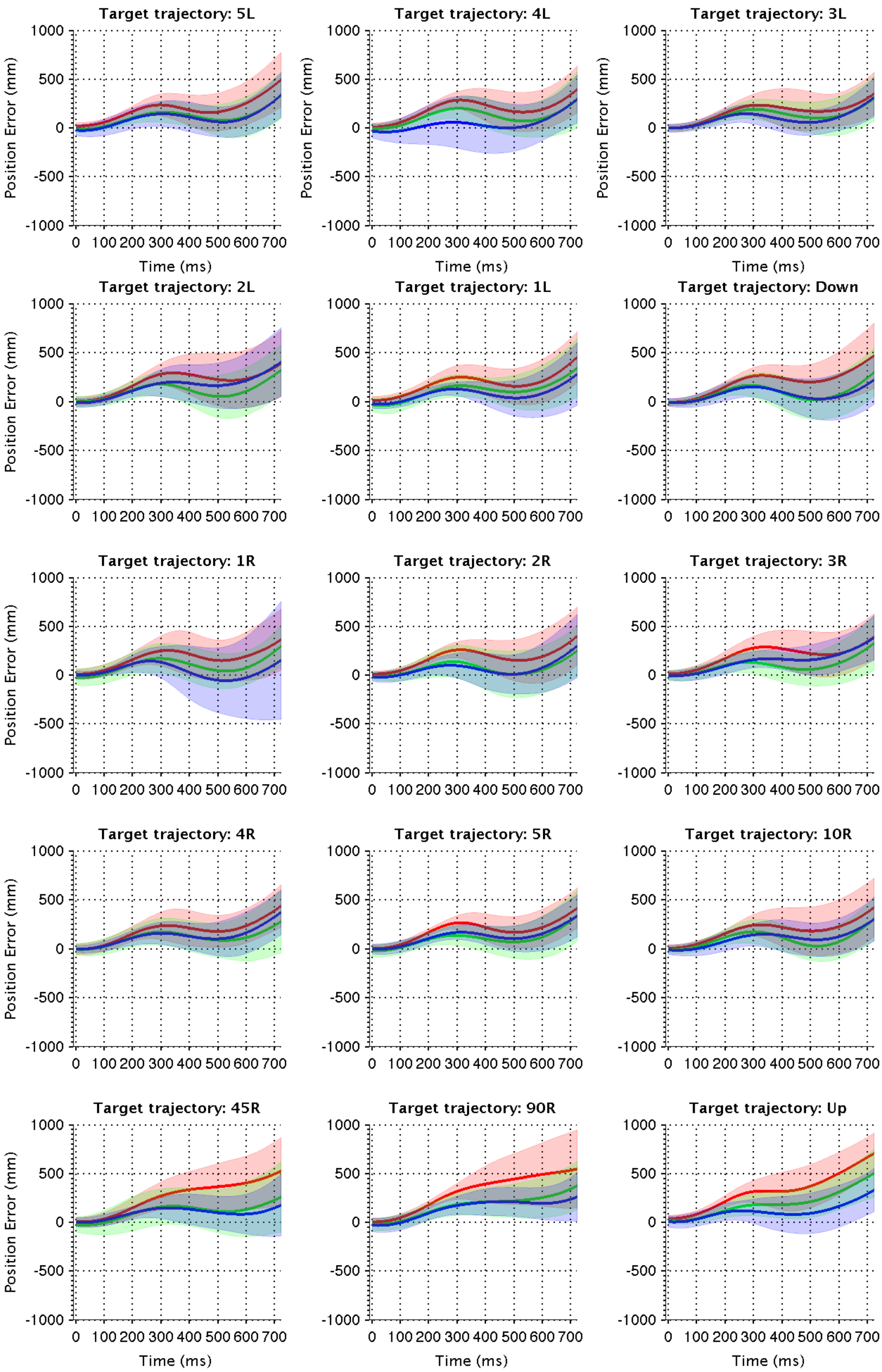


Figure 2-27. Time series of laser tracked in-line position error for each angle condition. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

Perpendicular to the direction of target movement (sideways)

Sideways tracking error in the laser the condition (Figure 2-28) was more similar within angles (at each attempt) and between attempts than was the case in the manual tracking condition (Figure 2-15). This was also seen in the angle data (Results 2.3.4.7). Further there appears to be less error in these data than in the manual and less change during the course of each time series.

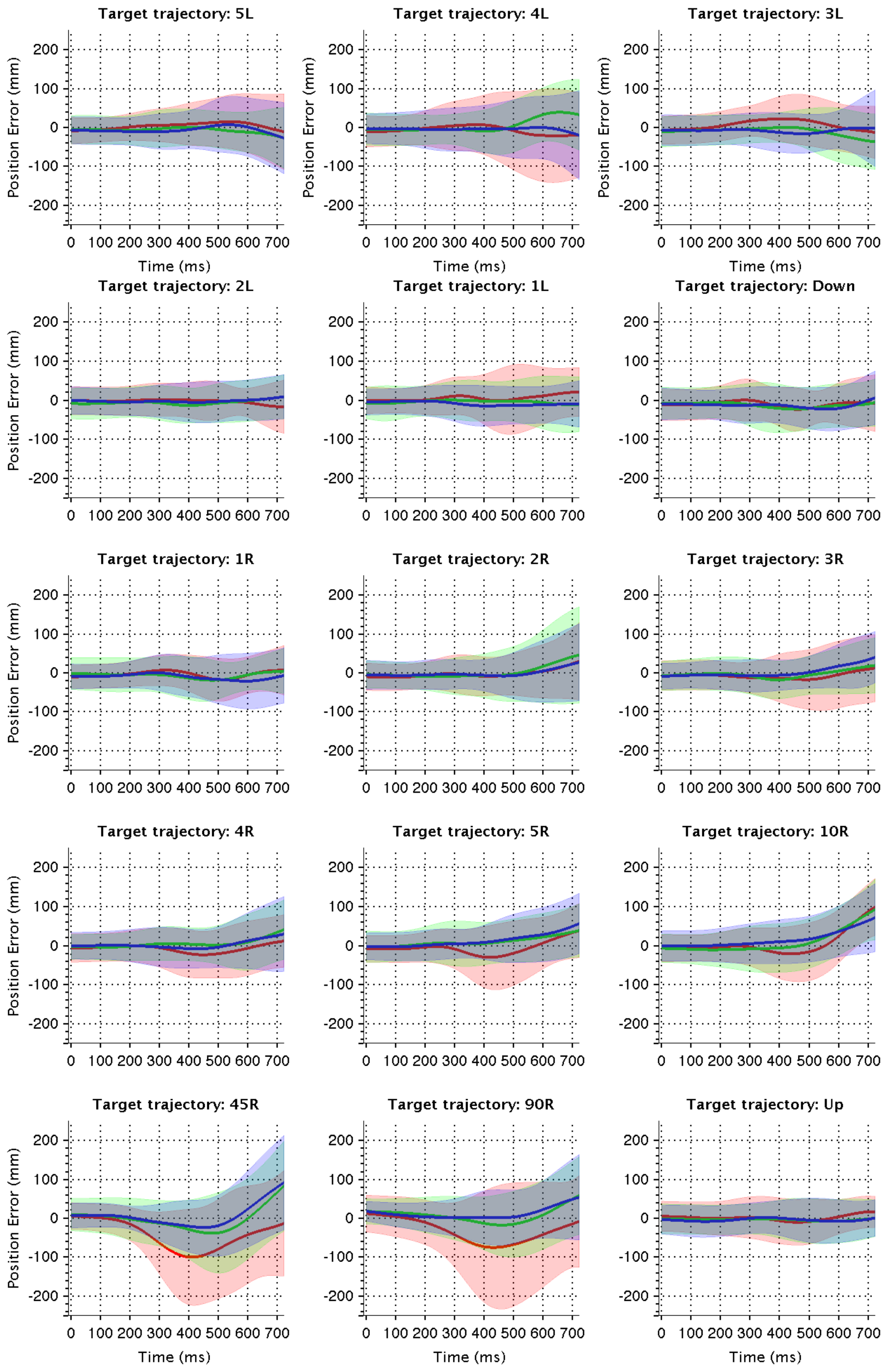


Figure 2-28. Time series of laser tracked sideways position error for each angle condition. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

2.3.4.4 Laser tracking: The effect of target angle on the in-line component of tracking

Total position error was significantly affected by the target path angle ($F(14,266)=4.202$, $p<.001$). Contrasts revealed vertically down error to be significantly different to 90° right ($F(1,19)=10.492$, $p=.004$) and vertically up ($F(1,19)=15.746$, $p=.001$).

Tracking was behind the target in every condition by roughly the same amount apart from 90° right and vertically up for which the tracking was significantly further behind vertically down (Figure 2-29). This tracking behind the target when pointing with the laser contrasts with the tracking ahead of the target seen during finger pointing (Results 2.3.3.4). The errors up to 90° are roughly twice the size of the errors seen in the manual condition though the size of the vertically up error is slightly reduced. Though standard deviations are typically smaller in the laser condition than they were in the manual condition, the increase in standard deviation as angle increases that was found in the manual condition is not present here.

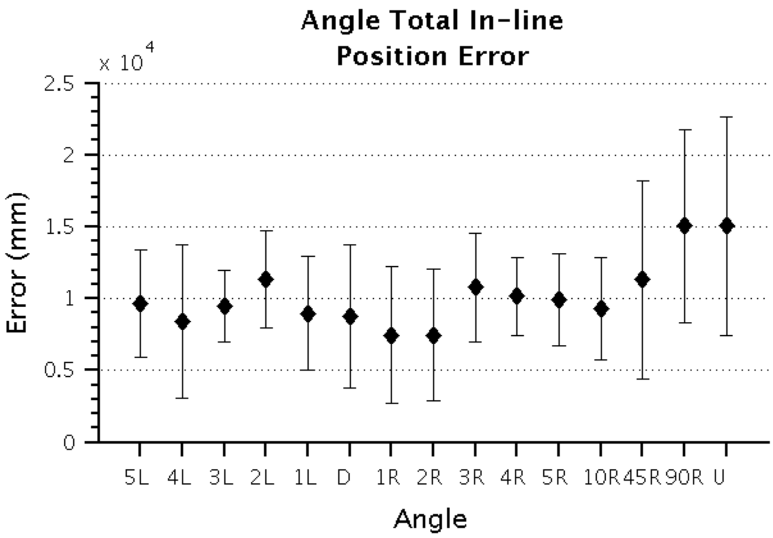


Figure 2-29. Laser tracking mean total position errors (with SD) along the line of target motion for different directions (angles).

Total velocity error was not significantly affected by the target path angle. Error SD was more variable for trajectories at >10º from the vertical but error means were fairly consistent (Figure 2-30).

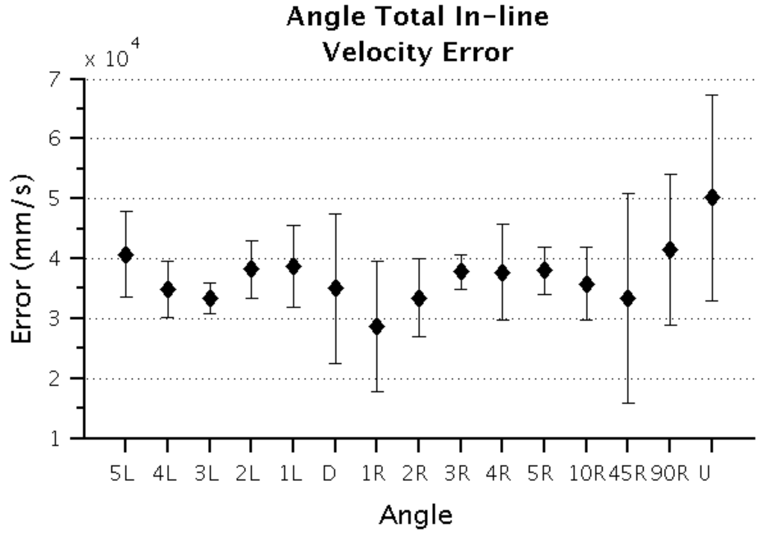


Figure 2-30. Laser tracking mean total velocity errors (with SD) along the line of target motion for different directions (angles).

Section Summary

In contrast to the manual condition, mean (angular) tracking errors in the laser condition showed that tracking was behind the target and that there was typically little difference in the total tracking errors at different angles. I suggest in discussion that control in this condition relies upon feedback from the laser spot rather than an internal model of target motion that appears to have been employed in the manual tracking condition.

2.3.4.5 Laser tracking: The effect of repetition (attempt no.) on the in-line component of tracking

Total position ($F(2,38)=74.506$, $p<.001$) and velocity errors ($F(2,38)=33.447$, $p<.001$) were significantly affected by tracking attempt. Contrasts revealed a significant difference from attempt 1 to attempt 2 (position: $F(1,19)=92.525$, $p<.001$; velocity: $F(1,19)=33.447$, $p<.001$).

Though tracking remained behind the target at every attempt, the distance behind was significantly reduced from the first to the second attempt, though there was no further significant reduction at the third (Figure 2-31). Velocity increased in accordance with this (i.e. always slower than the target but significantly less so by the second attempt with no further improvement at the third attempt).

The negative gradient is the same as in the manual condition (Results 2.3.3.5) but the signs of the errors are not. Laser tracking position is behind the target and slower than it in all attempts whereas in the manual condition only the first attempt is behind the target and all subsequent attempts are faster than it. The change in the error from first to second attempt was less in the laser condition than in the manual condition and the standard deviations at every attempt were smaller in the laser condition.

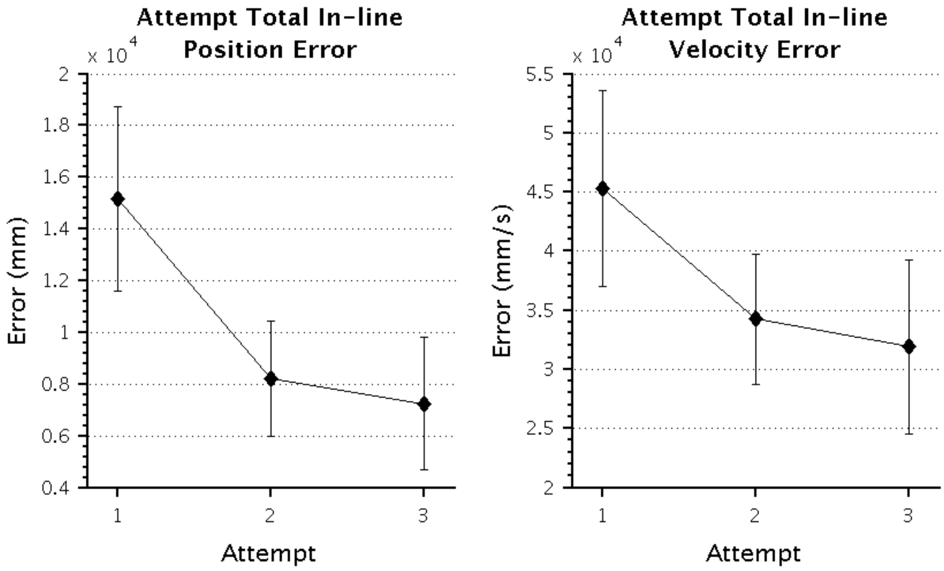


Figure 2-31. Laser tracking mean total position and velocity errors (with SD) along the line of target motion for the effect of repetition (attempt).

Section Summary

Tracking at each attempt was behind and slower than the target. As in the manual condition the errors were significantly reduced from the first to the second attempt though in the laser condition the difference was greater and SD at each attempt greater indicating greater improvement but also greater variability.

2.3.4.6 Laser tracking: Angle-attempt interaction on the in-line component of tracking

For total position error the results show that there may have been a significant interaction between the angle condition and the number of the attempt made (uncorrected $F(28,532)=1.856$, $p=.005$; GG $F(10.176,193.339)=1.856$, $p=.052$; HF $F(22.836,433.892)=1.856$, $p=.01$). Contrasts revealed a significant difference between the first and second attempt from vertically down to 3° left ($F(1,19)=5.313$, $p=.33$).

Across all angles, subjects tracked behind the target (Figure 2-32). At every angle the distance behind the target was reduced following the first attempt though there was typically little change from the second to the third attempt.

Contrasts revealed a significant reduction in error from first to second attempt for 3° left was less than that for vertically down. It appears that this result may arise from the fact that for 3° left the first attempt is low (indeed lowest) and the second attempt is a little high compared to other angles.

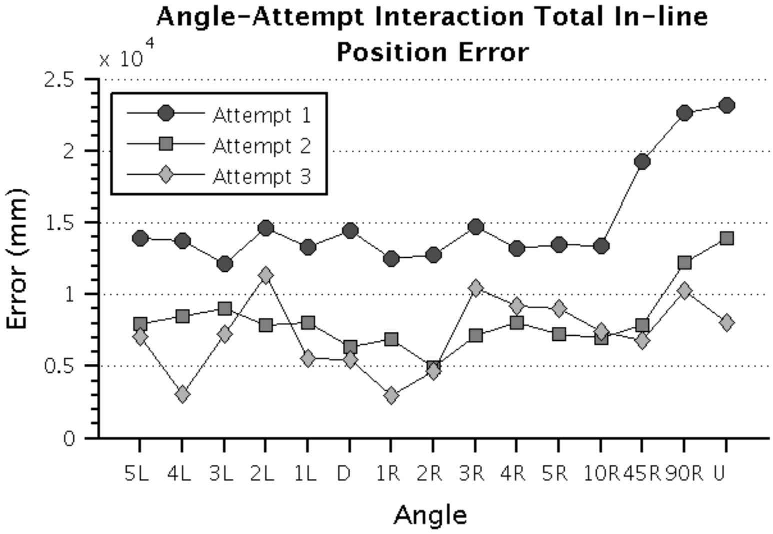


Figure 2-32. Laser tracking mean total position errors along the line of target motion for different directions (angles) and the effect of repetition (attempt).

For total velocity error the results show that there may have been a significant interaction between the angle condition and the number of the attempts made (uncorrected $F(28,532)=1.691$, $p=.016$; GG $F(9.095,172.806)=1.691$, $p=.094$; HF $F(18.163,345.093)=1.691$, $p=.039$). Contrasts revealed a significant difference between second attempt and third from vertically down to 3° right ($F(1,19)=4.969$, $p=.038$) and to 4° right error ($F(1,19)=4.593$, $p=.045$).

Velocity was typically increased from first to second attempt though was still slower than the target (Figure 2-33). Angles <2° and >10° shower further improvements from second to third attempt.

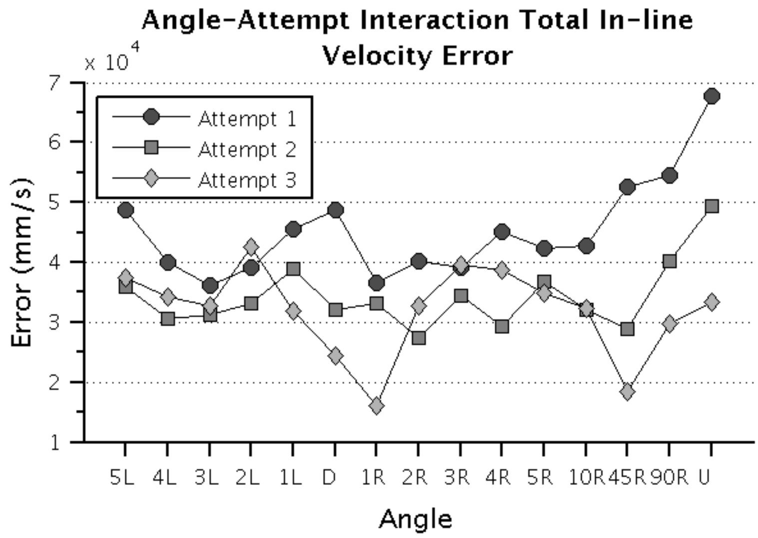


Figure 2-33. Laser tracking mean total velocity errors along the line of target motion for different directions (angles) and the effect of repetition (attempt).

Section Summary

Errors clearly reduced for all angles from the first to the second attempt and for tracking of targets moving horizontally or vertically upwards there appears to have been a further reduction at the third attempt whilst for other angles there is no clear change. In contrast to the manual condition there appears to be generally less change between mean errors but a clearer pattern of negative trend between attempts.

2.3.4.7 Laser tracking: The effect of target angle on the sideways component of tracking

Total position error was not significantly affected by the target path angle. All leftwards angles were negative (left of the target) and error means varied little but there is a positive gradient for rightwards angles' from 1° to 10° moving error means from left of the target to right of the target (Figure 2-34). Vertically up and vertically down have two of the smallest SDs and both have negative error means though vertically down has one of the largest error means of all angles. However it should be noted that if tracking is consistently to one side of the target trajectory then an offset of only 13.69 mm can create a total error of 1000 mm so the even relatively large error means with small SDs probably represent very small real deviations. Importantly this data indicates great consistency in tracking of a vertically descending target accelerating at *g*.

Total sideways position errors in the manual tracking condition at vertically up and at angles <45° were all approximately -1000 mm (approximately 1000 mm left of the target) and varied little though tracking at 45° right was significantly more leftwards (greatly negative error) than tracking at vertically down and at 90° tracking was only slightly more left than vertically down but had by far the largest SD of all tracking. In the laser condition there is greater variation between mean errors for angles from 5° leftwards to 10° rightwards. Tracking error means at 90° right and 45° differed from the main group of smaller angles less than was the case in the manual condition.

These data suggest feedback has the effect of bringing tracking at every angle to a roughly similar degree of success. However the much greater trial to trial variability at larger angular deviations from vertical (the SD for 90° is slightly smaller than in the manual condition but the SD for 45° is approximately twice as large) indicated that, as expected, the majority of the negative position error at angles 45° right and 90° was made up of first attempt error where the target trajectory was not known. Interaction effects (Results 2.3.4.8) confirmed this.

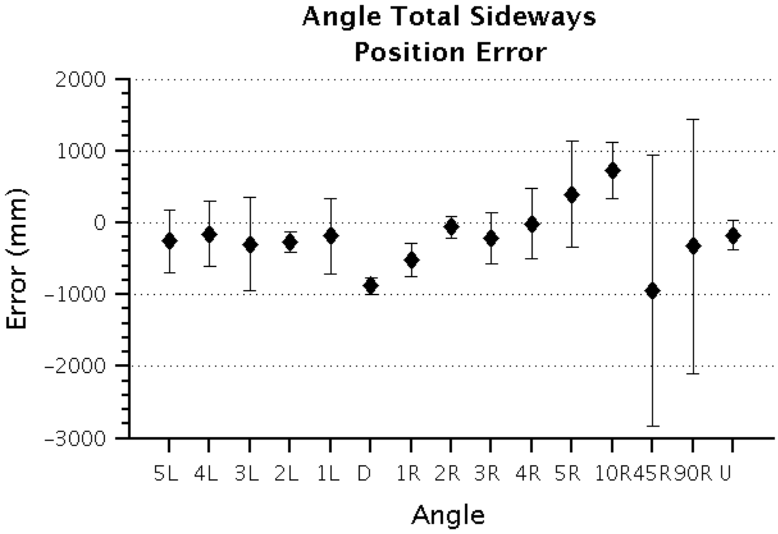


Figure 2-34. Laser tracking mean total position errors (with SD) perpendicular to the line of target motion for different directions (angles).

Total velocity error was significantly affected by the target path angle (F(5.899,112.071)=4.898, p<.001). Contrasts revealed vertically down to be significantly different to: 3° right error (F(1,19)=6.699, p=.018); 5° right error (F(1,19)= 31.054, p<.001); and 10° right error (F(1,19)=38.322 p<.001).

Tracking a target with a rightwards component to its movement resulted in an overall rightwards velocity error (Figure 2-35). That is, tracking at these angles moved to the right more than the target did. For leftwards angles only two of the five possible angle errors were negative (tracking moving more left than the target) whilst the remaining errors were positive (tracking moved towards the right than the target).

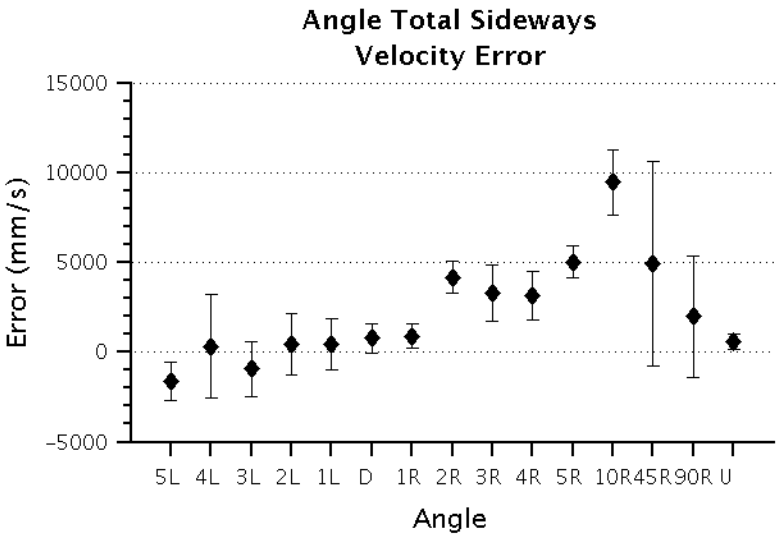


Figure 2-35. Laser tracking mean total velocity errors (with SD) perpendicular to the line of target motion for different directions (angles).

Total acceleration error was significantly affected by the target path angle

($F(6.652,126.39)=6.305, p<.001$). Contrasts revealed vertically down to be significantly different to: 3° left error ($F(1,19)=6.752$, $p=.018$); 4° left error ($F(1,19)=4.445$, $p=.048$); 5° left error ($F(1,19)=13.646$, $p=.002$); and 45° right error ($F(1,19)=8.264$, $p=.01$).

As with total velocity error there is a positive gradient from 5° left to 10° right though in this measure it is stronger and includes the error for tracking at 45° which is now the most positive value (Figure 2-36). Sideways acceleration errors indicate a change in the direction: positive errors indicate decreasing the speed of tracking left or increasing it right and vice versa for negative error.

All angles apart from leftwards angles ≥3° had positive tracking total acceleration errors and total velocity errors indicating an increasing rate of movement rightwards. Position errors at all of these angles apart from 5° and 10° right were negative which may indicate corrective movement. The acceleration and velocity errors for 3° and 5° leftwards were negative indicating an increasing rate of movement leftwards whereas tracking error for 4° leftwards was positive for velocity and negative for acceleration indicating a decreasing rate of movement rightwards. Position error at these three angles was negative which indicates that tracking at 3° and 5° leftwards was trying to catch the target whereas tracking at 4° leftwards was moving away from the target towards the vertical.

Clearly some meaning is lost or confused in the sum of the error derivations of position so it perhaps worth, at least for 2nd derivatives, examining the pattern of the time series data (Results 2.3.4) or the interactions between angle and attempt (Results 2.3.4.8) rather than these summed error.

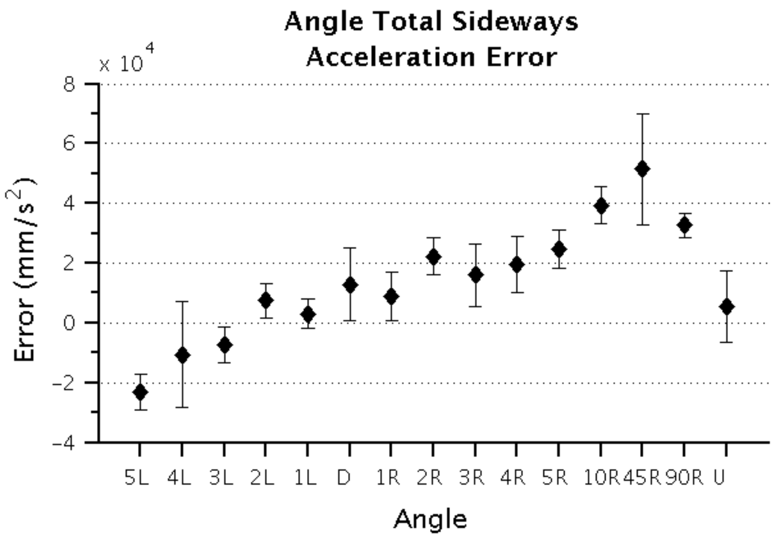


Figure 2-36. Laser tracking mean total acceleration errors (with SD) perpendicular to the line of target motion for different directions (angles).

Section Summary

Total tracking was generally to the left of the target but most angles showed some movement rightwards which may indicate a corrective movement.

2.3.4.8 Laser tracking: Angle-attempt interaction on the sideways component of tracking

For total position error the results show a significant interaction between the angle condition and the number of the attempts made (uncorrected $F(28,532)=3.270$, $p<.001$; GG $F(7.024,133.451)=3.270$, $p=.003$; HF $F(11.562,219.686)=3.270$, $p<.001$). Contrasts revealed a significant difference between attempt 1 and attempt 2 for 45° left error ($F(1,19)=7.161$, $p=.015$); and between attempt 1 and attempt 2 for 90° right error ($F(1,19)=5.591$, $p=.025$).

Angles <5° tended at the first attempt to be tracked insufficiently in the direction of target motion (i.e. preferred vertically down) and in subsequent attempts tracked too much in the direction of target motion (i.e. over compensation) (Figure 2-37). Tracking at the angles 45° and 90° right showed large leftwards errors in the first attempt which suggests, not unreasonably, that tracking was expected to be vertically down (or nearly so). Second and third attempts at these angles yielded roughly equal errors to those seen at the other rightwards angles.

The pattern here is roughly similar to that in the manual condition though these errors are approximately 50% of those in the manual condition. The greatest and most interesting difference between these two conditions is the reduction in tracking error to close to the level of most other angles by the second attempt at 45º when using the laser. When manual tracking there was very little change. I suggest reasons for this in Discussion.

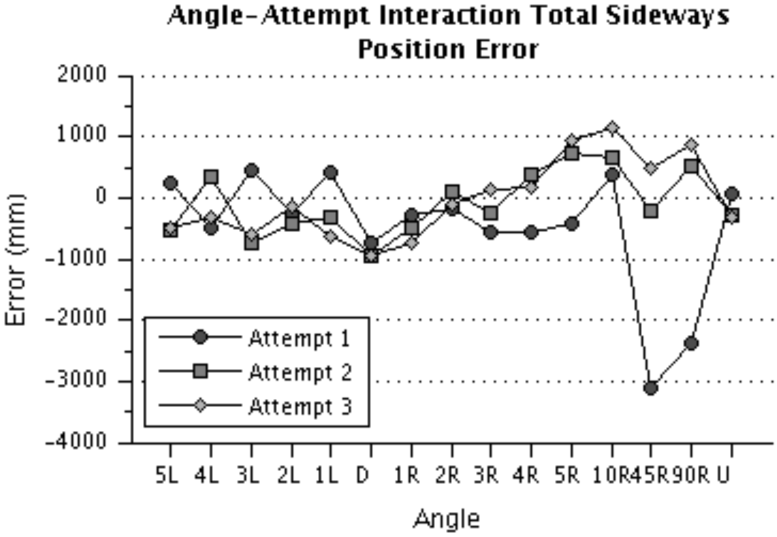


Figure 2-37. Laser tracking mean total position errors perpendicular to the line of target motion for different directions (angles) and the effect of repetition (attempt).

For total velocity error the results show that there may have been a significant interaction between the angle condition and the number of the attempts made (uncorrected $F(28,532)=2.441$, $p<.001$; GG $F(8.714,165.564)=2.441$, $p=.013$; HF $F(16.749,318.225)=2.441$, $p=.001$). Contrasts revealed a significant difference between attempt 2 and attempt 3 for 2° right error ($F(1,19)=4.489$, $p=.048$); between attempt 2 and attempt 3 for 4° left error ($F(1,19)=13.805$, $p=.001$); and between attempt 1 and attempt 2 for 45° right error ($F(1,19)=11.381$, $p=.003$).

Tracking at the first attempt of leftwards angles yielded sideways velocity errors that were typically negative though close to zero (Figure 2-38) meaning that tracking the horizontal component of target trajectory was well achieved. Second and third attempts tended to have larger error but without consistent direction of travel relative to the target. Errors at rightwards angles were typically greater than the equivalent leftwards angle at the first attempt and all were positive (right of the target). There is a positive gradient from 5° left to 5° right which might extend to 10° if scaling of angular change on the horizontal axis were equal. This gradient is bias towards positive values but is important in representing the general trend of sideways movement for tracking targets with a horizontal component.

Rightwards total position was typically left of the target however so perhaps the rightwards velocity is indicative of change in direction to compensate for this error. This would appear to be the case for 45° and 90° right error.

In the manual condition tracking at 1º left or right moved in the direction of the vertical and was opposite to the direction of movements at a larger angle at the same side (Results 2.3.3.7 and 2.3.3.8). There is no evidence of this here.

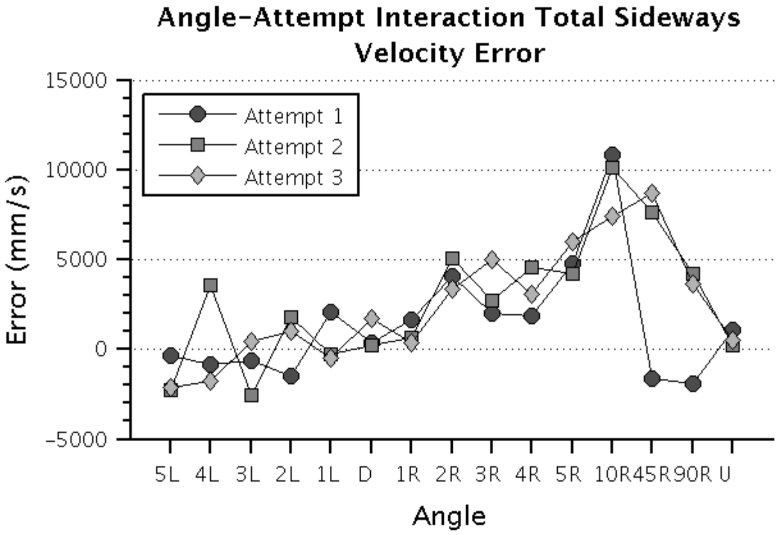


Figure 2-38. Laser tracking mean total velocity errors perpendicular to the line of target motion for different directions (angles) and the effect of repetition (attempt).

Section Summary

Tracking at each attempt was fairly consistent for each angle suggesting little or no change in tracking control or output. Unlike the manual condition there is no evidence of tracking towards the vertical when the target trajectory is 1º left or right.

2.3.5 Gaze only tracking

2.3.5.1 Gaze only tracking along the direction of target movement time series plots

The left hand side plots (Figure 2-39), especially the velocity plot, show clearly that on average (across all directions and participants) there was:

- An initial reaction time. There is a steady maintained vertical position (flat portion) with accompanying velocity and acceleration near zero at the start of each trace, though the length of this feature decreases slightly with practice.
- First catch-up saccade onset around 250 ms (in the position and velocity plots). This is clear in the tracked position and velocity as the first steep downward section, and in acceleration as the first large negative spike. It may be preceded by a short period of smooth pursuit (gentle slope in tracked position).
- Smooth pursuit from ~375 to ~525 ms. Tracking velocity drops and roughly matches target's.
- A second catch-up saccade around 525-650 ms. Seen clearly in sharp negative tracking velocity and acceleration spikes.

- Some smooth pursuit and falling behind at end of the 730 ms tracking period.
- Two downward acceleration 'peaks' are clearly visible in the acceleration plot at about 275 and 550 ms as the first and second saccade are generated.

The position error (top right panel) shows that by the third attempt the saccades are bringing gaze almost precisely to the predicted position of the target (near zero error). The third attempt, given the impossibility of the subject removing the initial reaction time, is close to perfect in bringing gaze to the anticipated location of the target on its trajectory after each saccade.

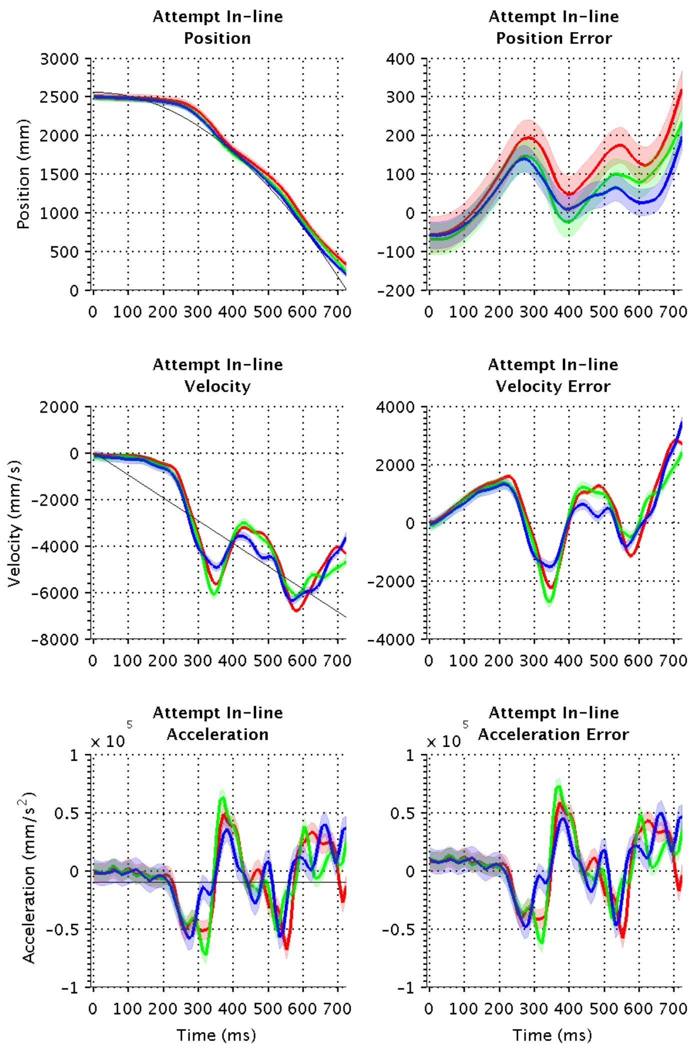


Figure 2-39. Time series of gaze tracked (in the gaze only condition) in-line position, velocity and acceleration for each attempt. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

2.3.5.2 Gaze only tracking: Trajectory plots

See Results 2.3.3.2 for a description of the plot components.

Tracking was typically behind the target and showed little or no sideways deviations for vertically descending or ascending targets (Figure 2-40). As with manual (Results 0) and laser (Results 2.3.4) tracking there was a tendency to track too much in the direction of target motion and for the magnitude of such error to increase as the angular deviation away from the vertical increased. The trajectory at 45° was similar to that in the manual (Figure 2-13) and laser (Figure 2-26) conditions but there was no downwards movement at the start of tracking. Gaze tracking at 90° rightwards moved in a diagonal direction and the final tracked sideways position was ~200 mm further downwards (in real world terms) than at the start (Figure 2-40). An expectation of descending movement would be rebutted following the first attempt and such expectation was not found at other angles so this finding may indicate that gaze tracking methodology did not cope with severe horizontal rotations of the eye in orbit. However, the deflection is small so I do not consider this a particular concern.

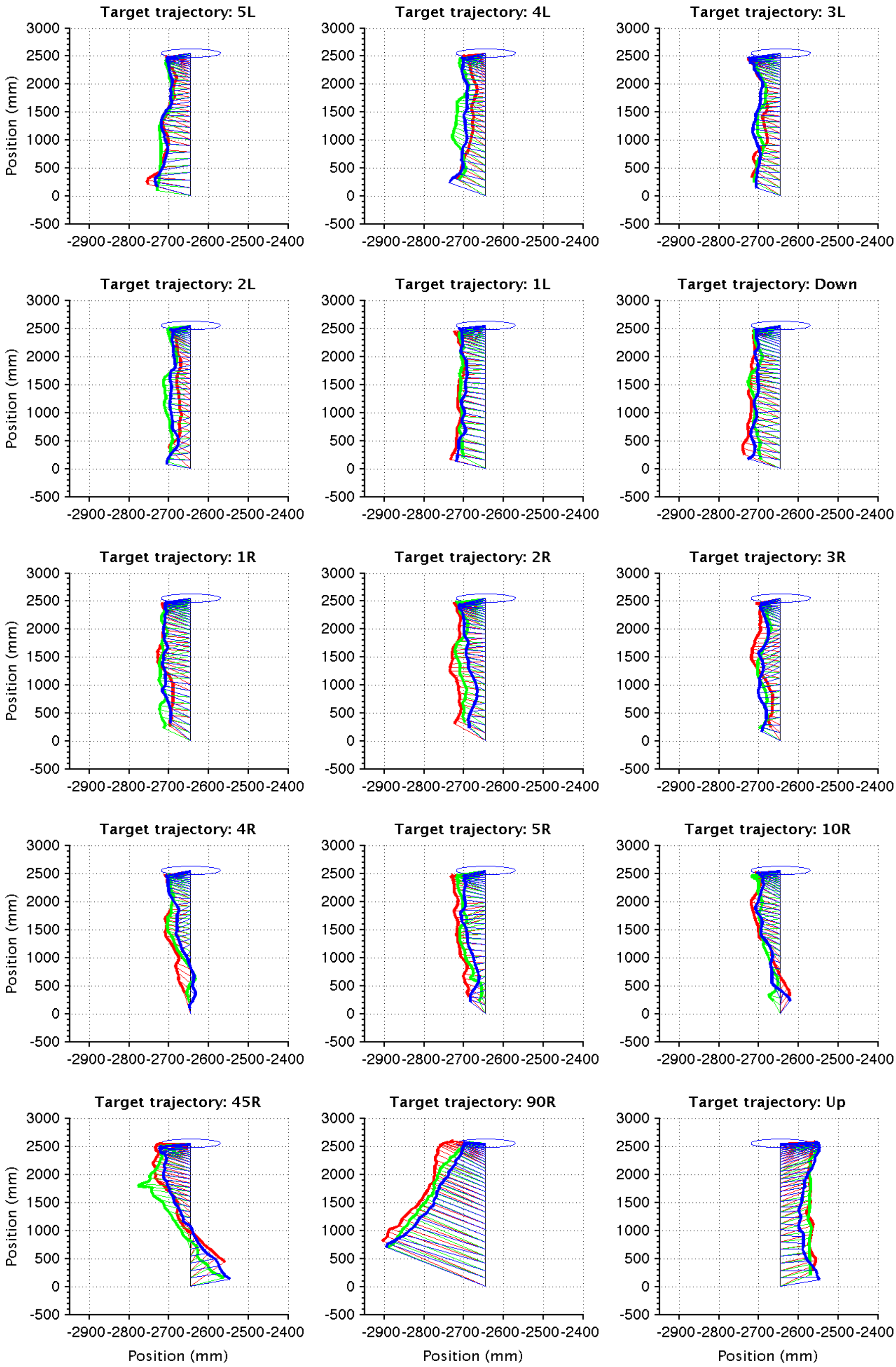


Figure 2-40. Trajectory plots of gaze tracking (in the gaze only condition) in each angle condition. Thick red, green and blue lines are the mean first, second and third tracking attempts and the thin black is the target's trajectory. Lines joining tracked trajectory to target trajectory are indicate position at every odd sample number.

2.3.5.3 Gaze only tracking: Time series of tracked position error for individual target directions

Along the direction of target movement (in-line)

For all angular deviations <90º there is a similar pattern for all time series (Figure 2-41). From the start of target movement gaze falls behind the target's parallel position but the first saccade at ~290 ms brings gaze back close to zero error. The time from the start of movement to this first saccade typically decreases with practice. After the catch-up saccade tracking falls behind the target. This timing of the first saccade at each attempt at each angle is similar to timing of movements in the manual (Figure 2-14) and laser (Figure 2-27) conditions. However in those conditions there was only clear evidence for a single movement whereas in the gaze only condition tracking appears to be made up of at least two saccades. The timing of the second saccade is typically between 500 and 600 ms from the start of the movement and again reduces the tracking error. Following this the error again increases as tracking falls behind the target. A general feature of these time series' is that the error appears to lower with practice though the interaction effects (Results 2.3.5.6) revealed that there was actually little difference between the attempts within each angle.

Tracking vertically upwards appeared to be generally similar to tracking vertically downwards though there was less evidence of second saccade. When tracking horizontally there is evidence of a small first saccade at ~300 ms. This is clearest in the first attempt but also appears in the second and third attempts as a reduction in the rate of increase of error (i.e. a reduction in positive gradient). Following this there appears to be a steady increase in error as tracking falls increasingly behind the target.

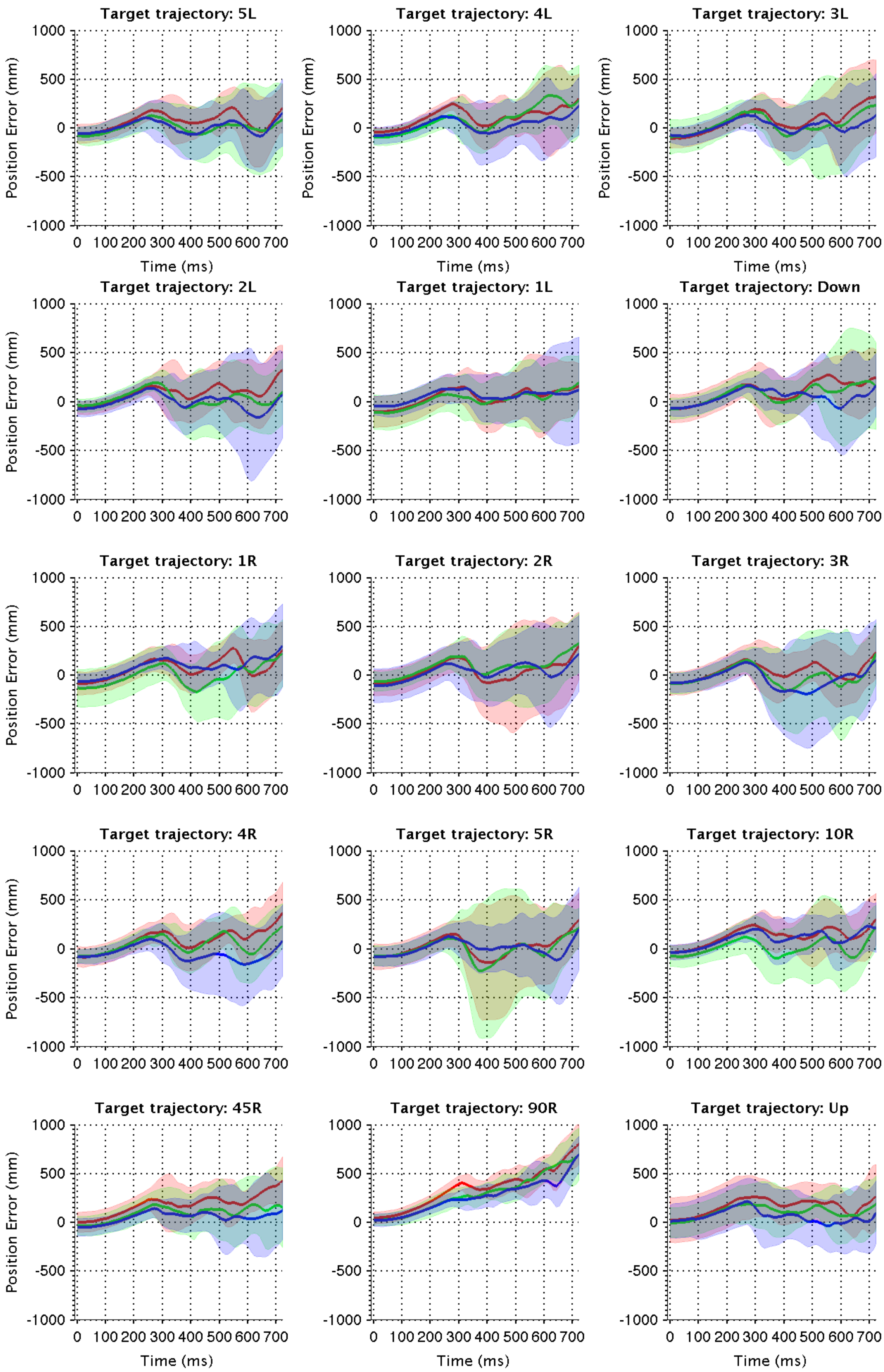


Figure 2-41. Time series of gaze tracked (in the gaze only condition) in-line position error for each angle condition. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

Perpendicular to the direction of target movement (sideways)

There was a sideways offset in gaze tracking (Figure 2-42) that is also clear in the angle (Results 2.3.5.7) and the interaction (Results 2.3.5.8) data presented later. At 1 ms the manual (Results 2.3.3.1) and laser (Results 2.3.4) tracking was close to zero error for all attempts at every angle whereas in the gaze only condition (Results 2.3.5) there is approx. -50 mm error for all attempts at all angles apart from when tracking vertically upwards when the error is approaching +100 mm. Positive error for vertically up is also evidence of a leftwards offset because pre counter-rotation (i.e. in real world coordinates) the tracking error up vertically upwards would be negative (see Results 2.2.8 and the pull out section at the end of this thesis).

Despite the difference in values, the pattern of the error in Figure 2-42 is similar to that in the manual and laser conditions in that at the end of the time series there tends to be a negative gradient for leftwards angles and a positive gradient for rightwards angles <90º and that this gradient tends to steepen as the angular deviation away from vertically down increases. Also for these angles, the difference from the starting error to final error (approx. 50 mm) is similar to the laser and manual conditions.

The tracking of targets moving diagonally (45º right) and horizontally (90º right) seem to have been special cases because the pattern of error differs considerably from that for other angles in this condition and from the same angles in the manual and laser conditions.

At 45º right in the laser and manual conditions the difference from starting error to final error after practice (i.e. attempts 2 and 3) was approximately 100 mm and the final error was more positive than the start error. Crucially the time series trace was different at attempt one to attempts two and three. In the gaze only condition the time series trace was similar for all angles and though there was a positive gradient towards the final error (as in the manual and laser conditions), the difference from the start to the final error was ~200 mm. In real world terms this means that towards the end of tracking time, gaze was moving more horizontally than the target after a period where error was not increasing (though was offset).

Tracking at 90º was especially unusual in this condition. In the manual and laser conditions there was an increasing error followed by a decreasing negative error. In real world terms this represents tracking downwards and then tracking increasingly horizontally to compensate for error as the target trajectory is realised. In subsequent attempts the error is kept close to zero. In the gaze only condition there was no difference between the attempt errors at this angles as all trajectories followed the same pattern though there appears to be a small decrease in the error throughout the time series at the second and third attempts compared to the first. The rate at which negative error increased throughout tracking suggests that there was an expectation that the target was moving on curve rather than a straight line even after practice.

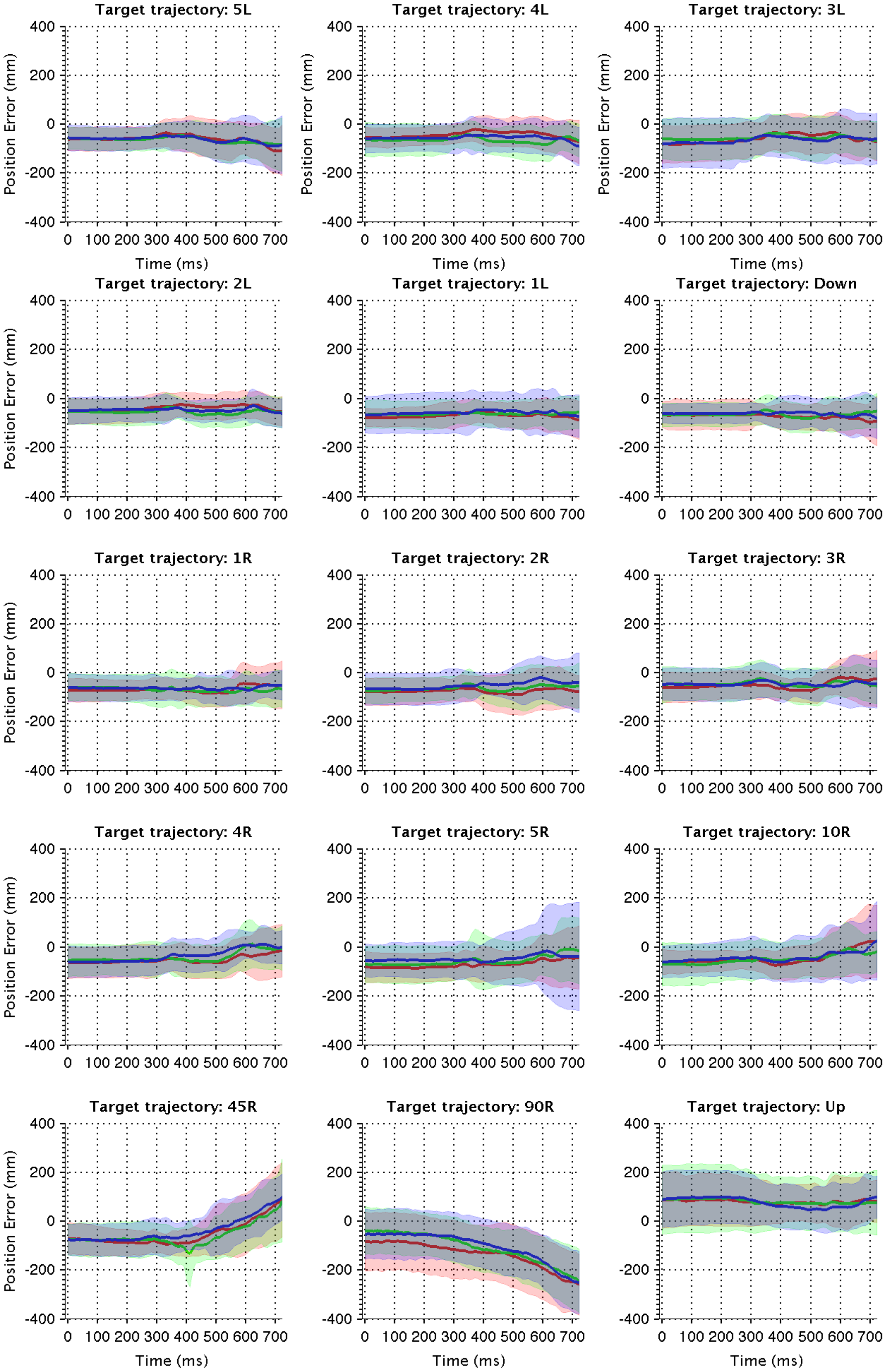


Figure 2-42. Time series of gaze tracked (in the gaze only condition) sideways position error for each angle condition. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

2.3.5.4 Gaze only tracking: The effect of target angle on the in-line component of tracking

Total position error was also significantly affected by the target path angle (uncorrected $F(14,168)=6.878$, $p<.001$; GG $F(4.982,59.788)=6.878$, $p<.001$; HF $F(8.945,107.336)=6.878$, $p<.001$). Contrasts revealed vertically down to be significantly different to 90° right ($F(1,12)=43.342$, $p<.001$).

With the exception of 3° right the tracking error at every angle was behind the target (Figure 2-43). Tracking at 3º right was marginally ahead of the target and 5R was only marginally behind. Tracking at 10° right, 45° right and vertically up resulted in errors that were larger than when tracking at the smaller angular deviations from vertically down, but the increase was not significant at the 5% level. Tracking at 90° (horizontally rightwards) was significantly further behind the target than when tracking vertically down (p<.001). In fact tracking horizontally resulted in error that was more than twice the size of error seen at all other angles.

This pattern is similar to those seen for manual (Figure 2-16) and laser (Figure 2-29) tracking though there was less within-angle variability in the laser condition than when tracking manually. In gaze only tracking there was even less within-angle variability than in the laser condition suggesting even greater consistency. The sign of the errors is more similar to the laser tracking condition (i.e. generally behind the target) though the size of the error at each angle is (with the exception of 90º right error) is around half of those seen with laser tracking.

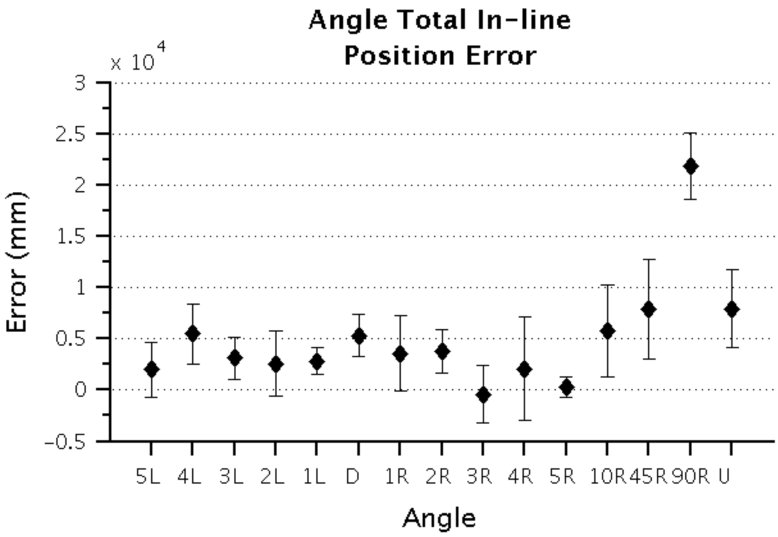


Figure 2-43. Gaze tracking (in the gaze only condition) mean total position errors (with SD) along the line of target motion for different directions (angles).

Total velocity error was significantly affected by the target path angle (uncorrected $F(14,168)=3.745$, $p<.001$; GG $F(5.282,69.942)=3.745$, $p=.003$; HF

$F(11.953,143.440)=3.745$, $p<.001$). Contrasts revealed vertically down to be significantly different to 90° right ($F(1,12)=22.195$, $p=.001$).

There is no clear pattern across the different angles of tracking except that velocity error when tracking rightwards was about twice the size of errors seen at all other angles (Figure 2-44). Tracking at every angle was slower than the target (positive error).

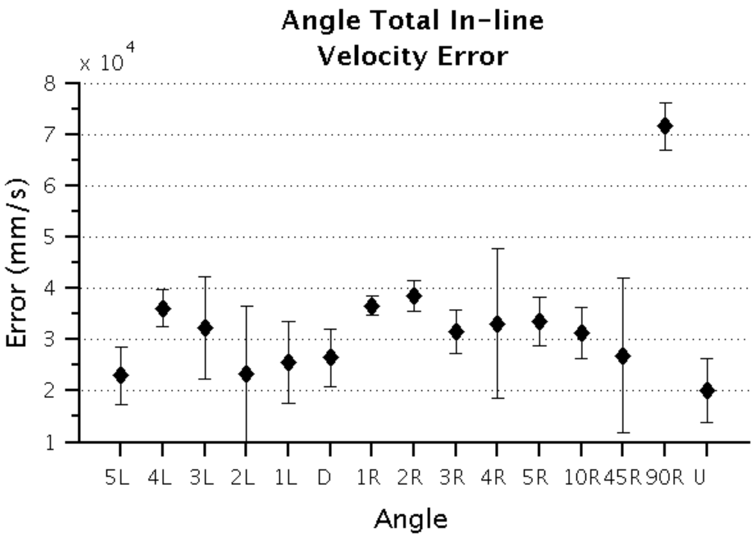


Figure 2-44. Gaze tracking (in the gaze only condition) mean total velocity errors (with SD) along the line of target motion for different directions (angles).

Section Summary

Tracking was behind the target overall. There was no difference between the angle errors apart from at 90º rightwards when tracking was further behind and slower than tracking at every other angle. The small SD at this angle is comparable to SD at other angles suggesting great consistency at all angles (i.e. little or no change between attempt errors) – this was not the case when manual tracking. In Discussion I consider whether tracking control at 90º rightwards was impaired or whether tracking was more difficult to execute horizontally.

2.3.5.5 Gaze only tracking: The effect of repetition (attempt no.) on the in-line component of tracking

Total position ($F(2,24)=7.424$, $p=.003$) and velocity errors ($F(2,24)=8.194$, $p=.002$) were significantly affected by tracking attempt. In both cases contrasts revealed a significant difference from the first to second attempt (position: $F(1,12)=7.51$, $p=.017$; velocity: $F(1,12)=6.419$, $p=.026$).

Tracking always remained behind the target but the distance behind reduced significantly (p=.017) from first to the second attempt and reduced further, though not significantly, to the third attempt (Figure 2-45). Accordingly the velocity remained less than the target but increased significantly (p=.026) from the first to the second and non-significantly to the third attempt (Figure 2-45). Though the mean errors are lower than the laser condition, the SDs are larger which will be because there is greater between angle variability in the gaze only angle total position caused by a relatively large error at 90º.

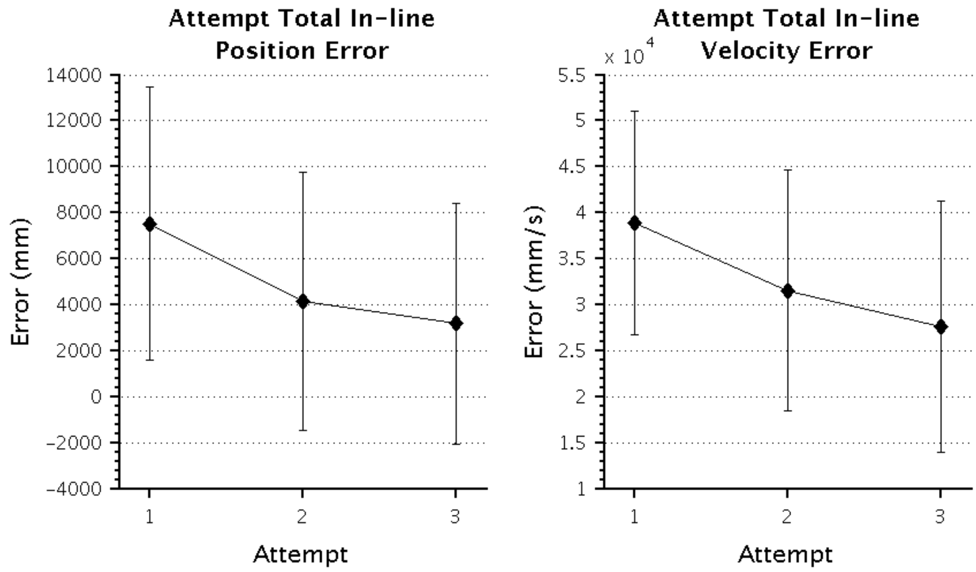


Figure 2-45. Gaze tracking (in the gaze only condition) mean total position and velocity errors (with SD) along the line of target motion for the effect of repetition (attempt).

Section Summary

Mean errors were lower than in the laser condition though tracking was still behind the target. Reductions in error suggest improvement in tracking for all angles.

2.3.5.6 Gaze only tracking: Angle-attempt interaction on the in-line component of tracking

For total position error there was no significant interaction between the direction of target motion and the number of the attempt made (uncorrected F(28,336)=1.431, p=.076; GG F(6.55,78.6)=1.431, p=.208; HF F(15.257,183.08)=1.431, p=.135).

There is as expected (from analysis of improvement with attempt number across all angles pooled, see Results 2.3.4.4) a tendency across all angles (though perhaps clearer at angles >10°) that tracking position moved towards and occasionally overtook target position with repetition (Figure 2-46). The large SDs in the attempt error appears to be due to the error when tracking horizontally, which is considerably larger at every attempt, that all other errors. Also, the consistency of errors at each attempt within angles identified in the angle error is clear here.

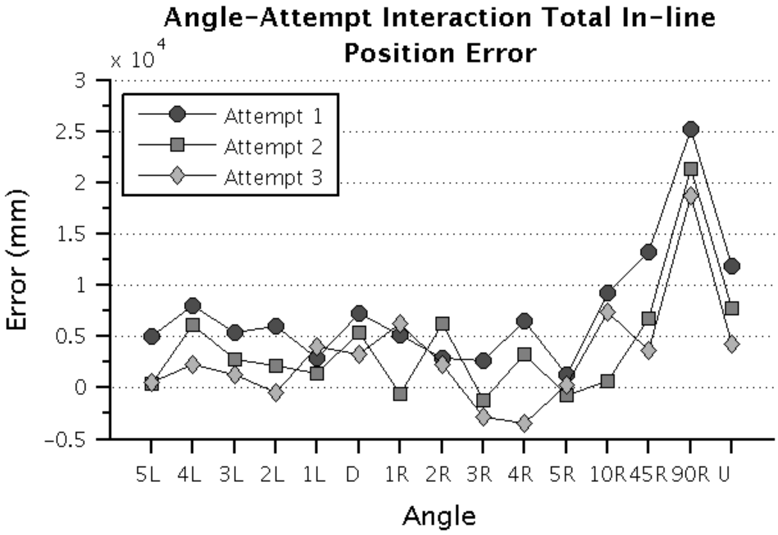


Figure 2-46. Gaze tracking (in the gaze only condition) mean total position errors along the line of target motion for different directions (angles) and the effect of repetition (attempt).

Section Summary

Tracking was typically behind the target overall and the distance behind was less than when laser tracking. There was a small but clear reduction in gaze tracking error from attempt one to attempts two and three when tracking >2° leftwards, >3° rightwards or vertically upwards. As in the manual condition the attempt errors within each did not change considerably but the pattern of errors is rather different. When gaze tracking the total errors when tracking a trajectory descending targets <45° were very similar but they larger for diagonal and ascending targets. Tracking horizontally yielded extremely large errors.

2.3.5.7 Gaze only tracking: The effect of target angle on the sideways component of tracking

Total position error was significantly affected by the target path angle (uncorrected $F(28,336)=8.295$, $p<.001$; GG $F(5.745,68.944)=8.295$, $p<.001$; HF $F(11.622,139.46)=8.295$, $p<.001$). Contrasts revealed vertically down to be significantly different to: 2° left ($F(1,12)=7.842$, $p=.016$); 3° right ($F(1, 12) = 6.169$, $p=.029$); and vertically up ($F(1,12)=16.946$, $p=.001$). Contrasts approaching significance were at 4° right ($F(1,12)=4.722$, $p=.051$) and 10° right ($F(1,12)=4.682$, $p=.051$).

Apart from vertically up all tracking was to the left of the target (after counter-rotation by target angle to bring target direction to vertically down) (Figure 2-47). Note that for the 90º right trajectory, left of the target after counter-rotation is below the target in real world coordinates. Sideways error when tracking 90° right was greater than error at the other angles.

Like in the manual tracking condition (Results 2.3.3.7), tracking in the gaze only condition was typically negative (left of the target) though unlike the manual tracking condition the tracking at vertically up was here positive (left of the target pre-counter-rotation) by more than the amount seen for most of the remaining angles. The size of the gaze only errors is considerably greater than in the manual tracking and laser tracking.

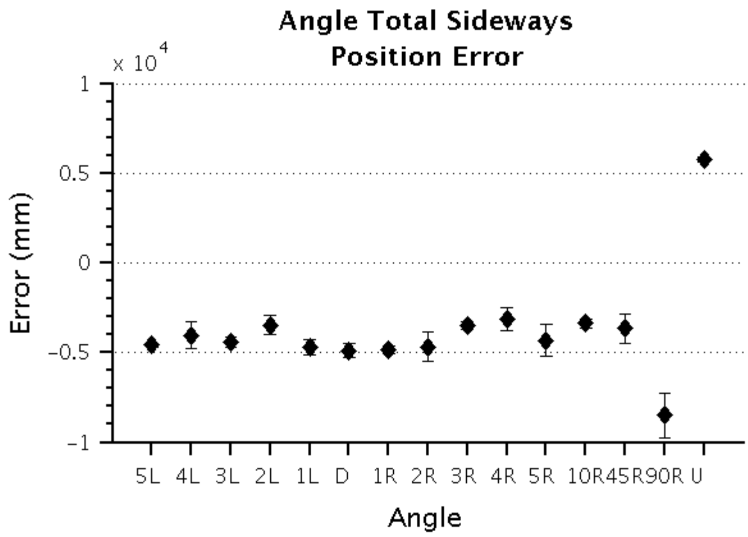


Figure 2-47. Gaze tracking (in the gaze only condition) mean total position errors (with SD) perpendicular to the line of target motion for different directions (angles).

Total velocity error was significantly affected by the target path angle (uncorrected $F(28,336)=16.461$, $p<.001$; GG $F(5.679,68.144)=16.461$, $p<.001$; HF $F(11.362,136.343)=16.461$, $p<.001$). Contrasts revealed vertically down to be significantly different to: 4° right ($F(1,12)=8.866$, $p=.012$); 10° right ($F(1,12)=11.086$, $p=.006$); 45° right ($F(1,12)=26.977$, $p<.001$); and 90° right ($F(1,12)=33.482$, $p<.001$).

At angles of 3° or less and for vertically up the tracking velocity error was near to zero (Figure 2-48). As the angle increased beyond 3° left the error became negative (gaze velocity more leftwards than target velocity) and as the angle increased beyond 3° rightwards to 45° rightwards the error became increasingly positive (gaze velocity more rightwards than target velocity). This means that past 3° in either direction there was a tendency to track sideways with a greater velocity than the target and in the direction of the angle condition. This may reflect the need in spatial terms, following the reaction time delay, to catch up with the sideways deviation of the target away from vertically down (see time series: Results 2.3.5). However, the error when tracking the horizontally rightwards moving target was negative (left more than the target. N.B. real world downwards) and was the largest error.

This pattern is roughly similar to that seen in the manual tracking condition and to a lesser extent that in the laser tracking condition. The 45° right and 90° right errors are not similar though, here being large and with opposite signs.

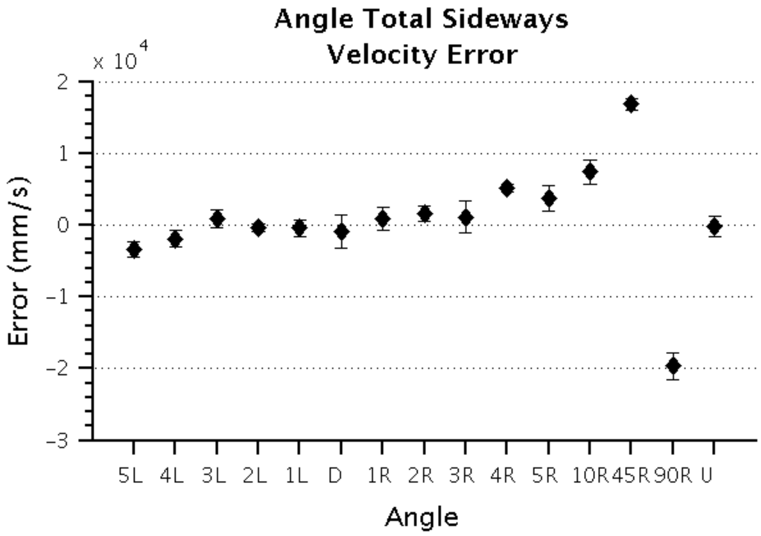


Figure 2-48. Gaze tracking (in the gaze only condition) mean total velocity errors (with SD) perpendicular to the line of target motion for different directions (angles).

Total acceleration error was significantly affected by the target path angle (uncorrected $F(28,336)=5.270$, $p<.001$; GG $F(5.253,63.038)=5.270$, $p<.001$; HF $F(9.825,117.905)=5.270$, $p<.001$). Contrasts revealed vertically down to be significantly different to: 1° left ($F(1,12)=4.821$, $p=.049$); 45° right ($F(1,12)=10.467$, $p=.007$); and 90° right ($F(1,12)=7.89$, $p=.016$).

With the exception of the error at 1° left which may be anomalous, there is no effect apart from when tracking a target moving at the angle of 45° right (large and positive) and 90° right (large and negative) (Figure 2-49). Positive errors indicate greater rightwards acceleration than the target and negative errors indicate greater leftwards acceleration than the target.

This pattern seen for gaze only tracking contrasts to the manual and laser tracking conditions where there was a strong positive gradient from 5° left to 90° right with tracking vertically down and vertically up at roughly zero acceleration error.

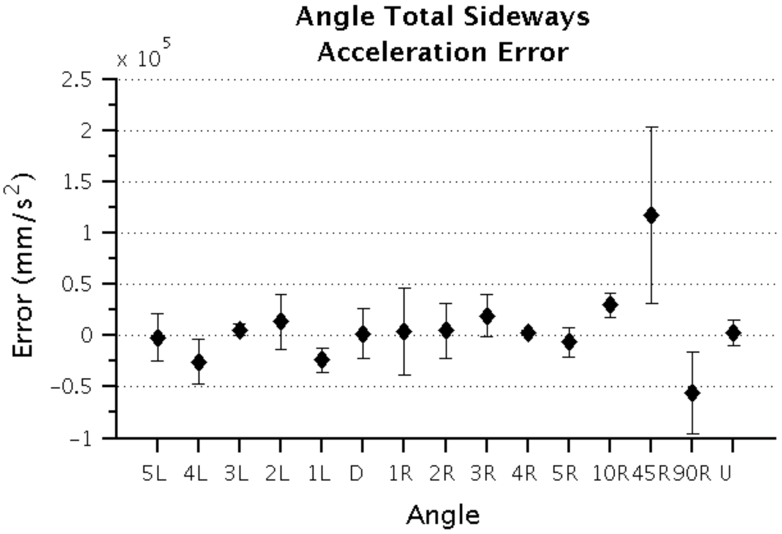


Figure 2-49. Gaze tracking (in the gaze only condition) mean total acceleration errors (with SD) perpendicular to the line of target motion for different directions (angles).

Section Summary

Evidence in the position error suggests that gaze intercept may have been offset to the left consistently by approximately 50 mm. This is examined thoroughly in Discussion but is small error that affects only the position measures and not its derived measures.

A consequence of the offset is that it appeared that tracking was consistently to the left of the target but the offset in mind the tracking error was actually likely to be very small for all angles apart from 90° which appears to have genuinely been tracked to the left of the target following counter-rotation. Vertically up appears to be tracked rightwards but the sign of this error which indicates tracking left or right of the target following counter-rotation can be considered opposite to what appears so in fact it was tracked approximately the same as vertically down. Tracking horizontally appears to have been tracked to the left of the target but prior to counter-rotation this would be vertically down (in real world coordinates) so this may represent an expectation of a descending target (rather than horizontally moving) target even with practice (small SD indicate consistent error).

2.3.5.8 Gaze only tracking: Angle-attempt interaction on the sideways component of tracking

No significant differences were found. The pattern of total position attempt errors within each angle condition does not vary (Figure 2-50).

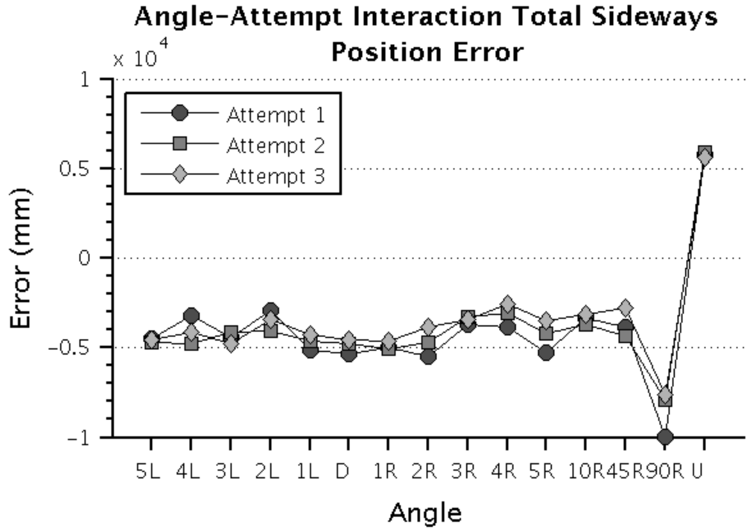


Figure 2-50. Gaze tracking (in the gaze only condition) mean total position errors perpendicular to the line of target motion for different directions (angles) and the effect of repetition (attempt).

Section Summary

As suggested by the angle data there was very consistent error at attempts within each angle. There is nothing new revealed by this data.

2.3.6 Gaze tracking in the manual condition

2.3.6.1 Gaze tracking in the manual condition along the direction of target movement time series plots

Time series of gaze tracking in the manual condition (Figure 2-51) shows a clear series of events common to all attempts:

- Tracking is ahead of the target by ~100 mm at the start of the time frame analysed but falls behind even with a short period of smooth pursuit.
- There is a first saccade between at ~325 ms at attempt one and ~275 ms at attempts two and three. This saccade reduces the positive error by ~100 mm, which brings position error to near zero for attempts two and three.
- A small saccade between approx. 450-500 ms slows the increasing position error following the first saccade.
- A third saccade at ~550 ms again slows the rate or error increase.

There is a clear difference from the first to the second and third attempts though saccade timings and patterns are similar. These results are similar to gaze only attempt time series as was expected following the similarities in the angle and attempt data.

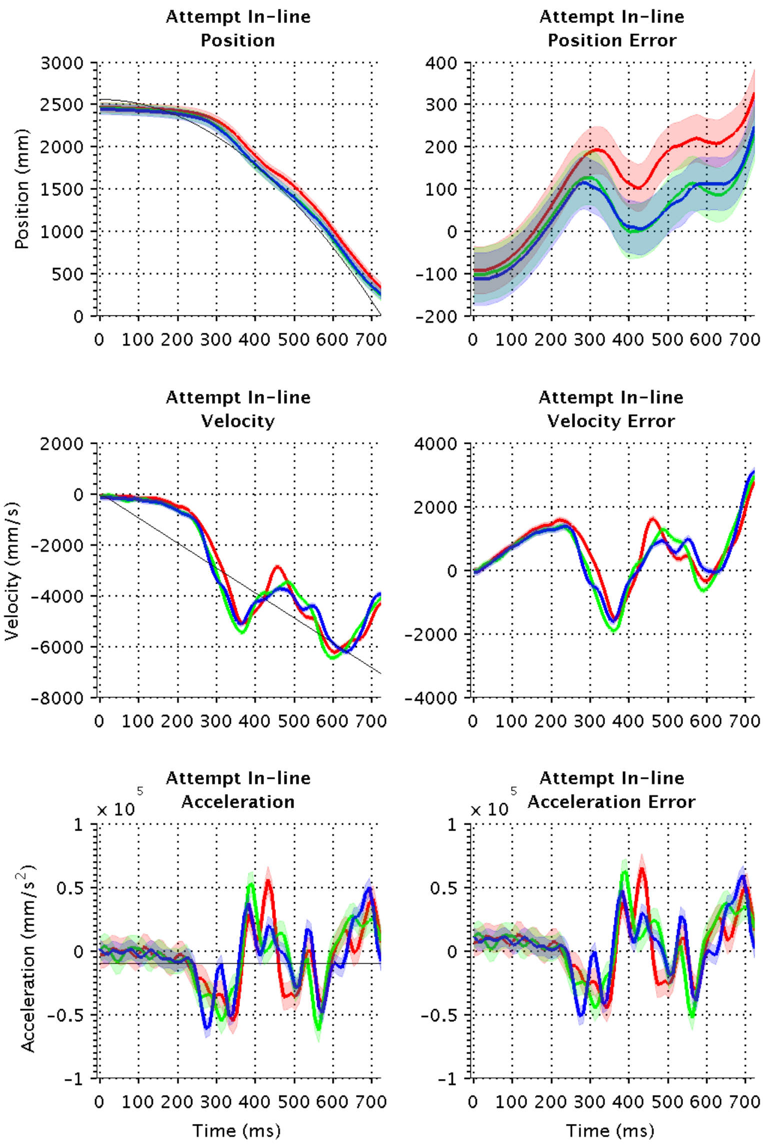


Figure 2-51. Time series of gaze tracked (in the manual condition) in-line position, velocity and acceleration for each attempt. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

2.3.6.2 Gaze tracking in the manual condition: Trajectory plots

See Results 2.3.3.2 for a description of the plot components.

Like in the gaze only condition (Results 2.3.5.2), gaze tracking in the manual condition appears to be behind the target for all angle conditions (Figure 2-52) and all features are similar to that condition apart from the tendency to track too much in the direction of target motion that has been clear in all previously examined tracking conditions. Here gaze tracking for leftwards moving targets was typically moving insufficiently leftwards relative to the starting tracked position (at 1 ms). Whereas for rightwards moving targets the tracked position was moving too much rightwards relative to the starting tracked position (at 1 ms). This is examined in greater detail in the sideways data sections (Results 2.3.6.7 & 2.3.6.8).

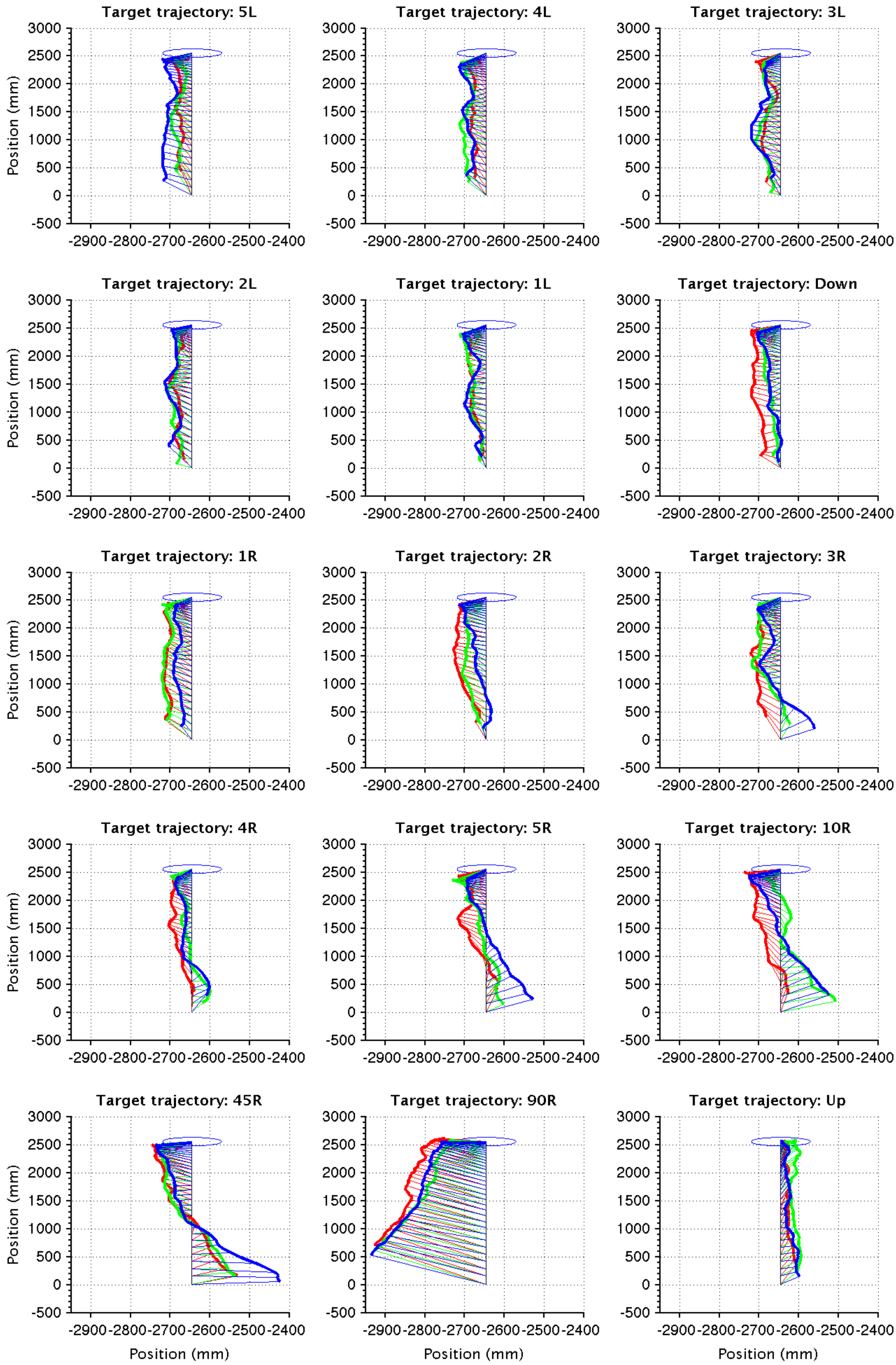


Figure 2-52. Trajectory plots of gaze tracking (in the manual condition) in each angle condition. Thick red, green and blue lines are the mean first, second and third tracking attempts and the thin black is the target's trajectory. Lines joining tracked trajectory to target trajectory are indicate position at every odd sample number.

2.3.6.3 Gaze tracking in the manual condition: Time series of tracked position error for individual target directions

Along the direction of target movement (in-line)

Tracking at 1 ms typically ahead of the target (negative in-line error) but fell behind throughout the trial (Figure 2-53). This probably represents tracking offset rather than tracking beginning early because the tracked velocity and acceleration at 1 ms are approx. zero (Figure 2-51). When tracking vertical ascending or descending trajectories or trajectories of <45º angular deviation from the vertical, the starting errors were typically approx. 100 mm ahead of the target (negative error) and these errors moved to behind the target before a first saccade at ~300 ms though the timing of this saccade typically decreased by between 50-100 ms from the first to third tracking attempt. Another common feature is a second saccade typically between 500-600 ms. As the angular deviation away from the vertical increased up to 10º, the position error increases over the time series especially at the first attempt.

The vertically up time series matches very closely that of vertically down though it does not have the -100 mm starting offset present at that angle and most angles <45º.

Tracking a target moving at 45º yields the most steady in-line position errors with the only clear long periods of zero increase in error between 400-500 ms for attempt 1 and 450-600 ms for attempt 3. This is probably not 'real' and is in fact likely to be a product of averaging because it is not present in at any other angle for any tracking method. Tracking the horizontally moving target (90º right) showed less clear saccadic events and though the overall error does decrease with practice, all errors are larger than at other angles.

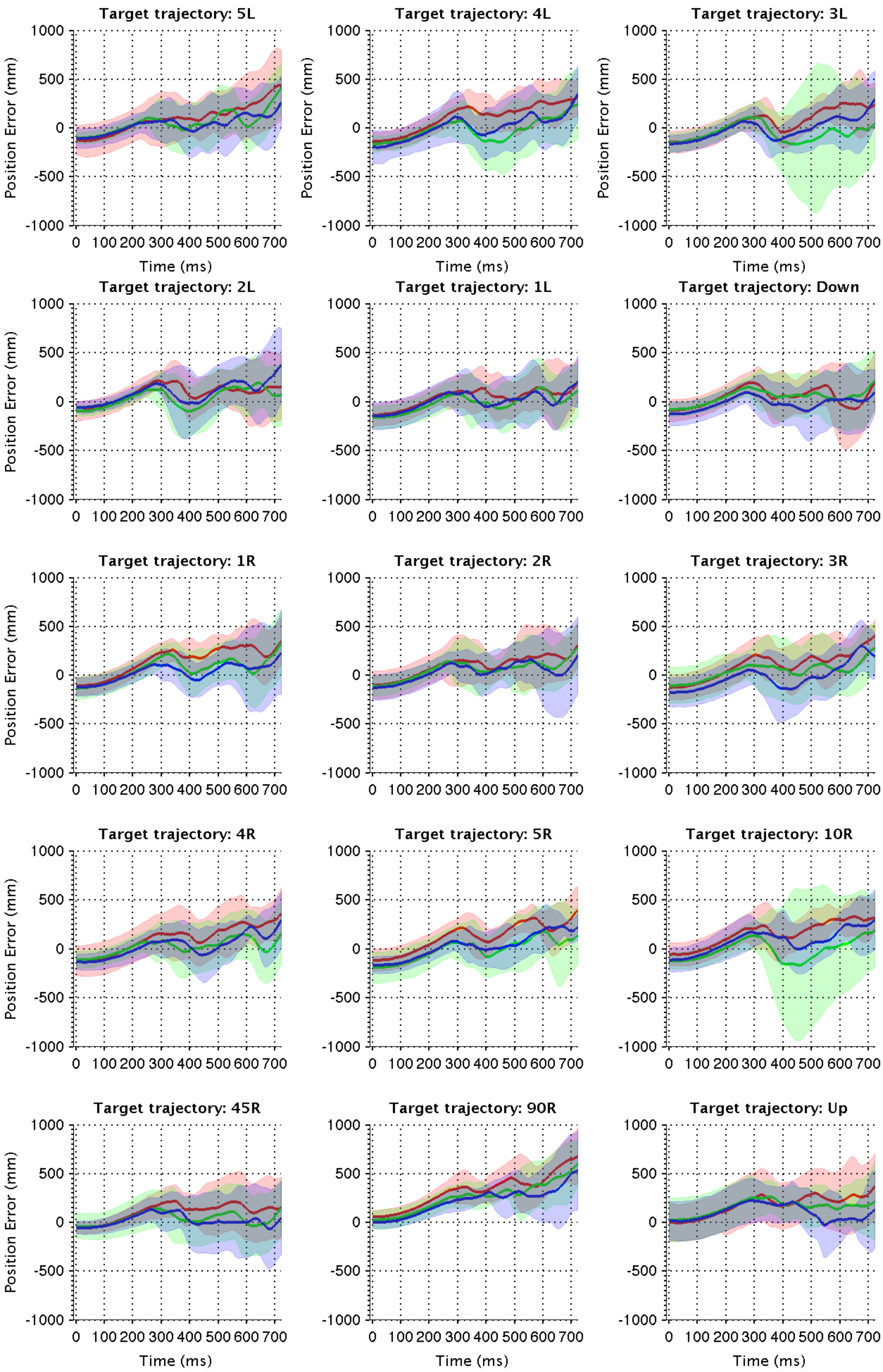


Figure 2-53. Time series of gaze tracked (in the manual condition) in-line position error for each angle condition. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

Perpendicular to the direction of target movement (sideways)

The starting error was between approx. -50 mm and -100 mm at every angle apart from vertically up where the starting error was close to zero (Figure 2-54). This is in contrast to gaze tracking in the gaze only condition where there was always an offset of ~100 mm to the left of the target in real world coordinates (i.e. +100 mm error for vertically up and -100 mm error for all other angles).

Tracking at all leftwards angles and rightwards angles <2º show small deviations suggestive of saccades but errors are generally steady. There is a positive gradient to the time series when tracking rightwards angles >1º and a negative gradient when tracking horizontally. Positive gradients indicate tracking moving rightwards and negative gradients indicate tracking leftwards. This is similar to patterns found in the manual (2.3.3.1), laser (2.3.4) and gaze only conditions (2.3.5).

The error pattern when tracking at 45º and 90º rightwards, though not typical of other error patterns in this tracking condition, matches the pattern found in the gaze only condition (Figure 2-42) for those angles.

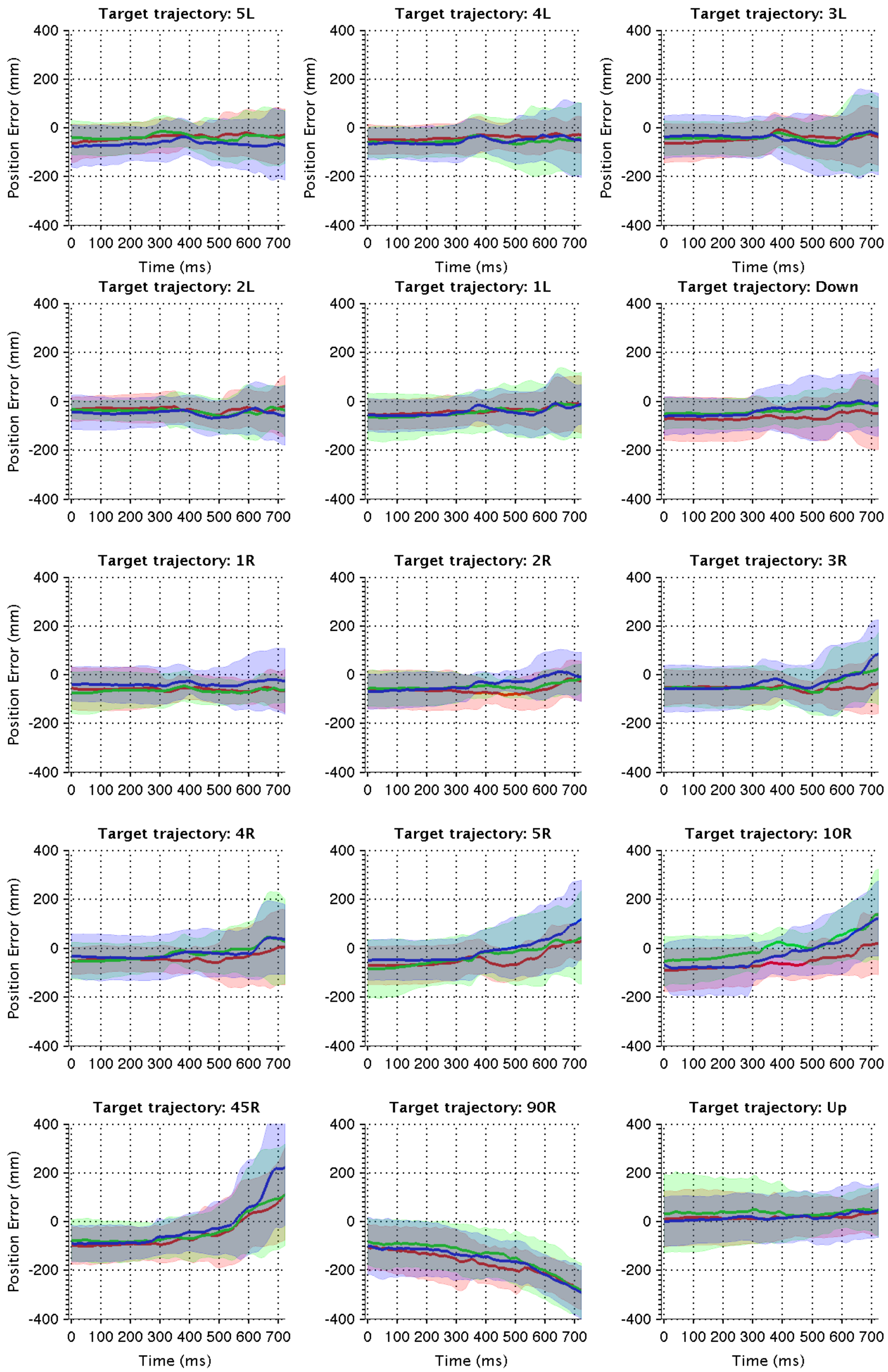


Figure 2-54. Time series of gaze tracked (in the manual condition) sideways position error for angle condition. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

2.3.6.4 Gaze tracking in the manual condition: The effect of target angle on the in-line component of tracking

Total position error was significantly affected by the target path angle (uncorrected $F(14,126)=4.375$, $p<.001$; GG $F(3.591,32.317)=4.375$, $p=.008$; HF $F(6.269,56.417)=4.375$, $p=.001$). Contrasts revealed vertically down to be significantly different to 90° right ($F(1,9)=85.34$, $p<.001$) and vertically up ($F(1,9)=7.148$, $p=.025$).

Tracking was always behind the target to an equal degree for all angles apart from 90° right and vertically up when it was significantly further behind vertically downwards tracking (Figure 2-55). Tracking by the pointing arm in the manual condition was ahead of the target, whereas tracking by the eyes in the gaze tracking only condition lagged behind. Here, gaze tracking during manual tracking (rather than in isolation) is most similar in pattern and mean scores to gaze tracking in the gaze only condition though the SDs are typically higher.

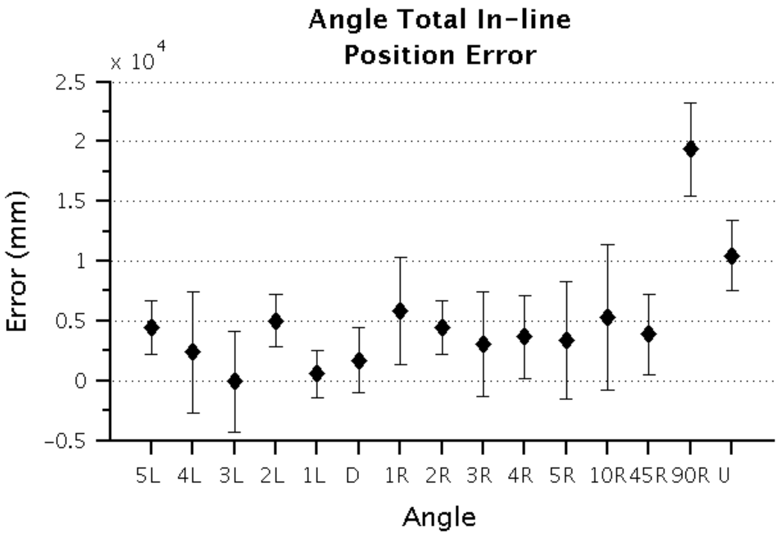


Figure 2-55. Gaze tracking (in the manual condition) mean total position errors (with SD) along the line of target motion for different directions (angles).

Total velocity error was significantly affected by the target path angle (uncorrected $F(14,126)=2.666$, $p=.002$; GG $F(4.213,37.914)=2.666$, $p=.045$; HF $F(8.382,75.437)=2.666$, $p=.011$). Contrasts revealed vertically down to be significantly different to: 1° right ($F(1,9)=5.748$, $p=.04$); 4° left ($F(1,9)=7.998$, $p=.2$); 4° right ($F(1,9)=6.13$, $p=.35$); and 5° left ($F(1,9)=6.646$, $p=.3$).

Velocities were always slower than the target (Figure 2-56). There is no consistent pattern to the error, though the value for vertically downwards is smaller than the values for other small angular deviations from vertical that have small SDs (2º left mean±SD = 28831.71±12756.43, vertically mean±SD = 29135.22±4373.12). As in the total position error, gaze tracking velocity results in the manual condition more closely matched those of gaze in the gaze only condition (slower than the target with little pattern) than those of the manual tracking (which were faster than the target with clearly patterned differences between angles). The errors here are in fact larger than those in the gaze only condition.

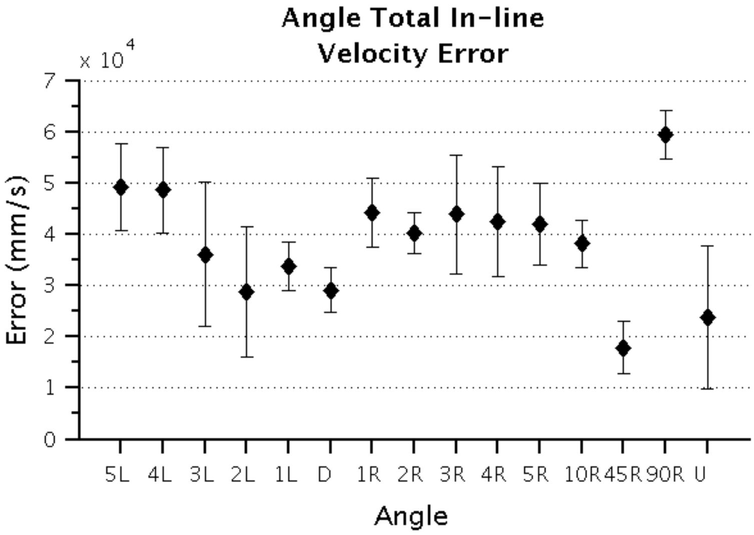


Figure 2-56. Gaze tracking (in the manual condition) mean total velocity errors (with SD) along the line of target motion for different directions (angles).

Section Summary

It might have been expected that gaze tracking in the manual condition would more closely resemble the manual tracking which led the target (i.e. that gaze would also typically be ahead of the target) rather than the gaze tracking in the gaze only condition which followed the target (i.e. typically behind the target) though this was not the case. In fact gaze tracking in the manual condition lagged slightly more behind the target than gaze tracking in the gaze only condition.

Manual tracking was typically ahead of and faster than the target but gaze in both conditions was typically behind and slower than the target. As in the gaze only condition the position error when tracking horizontally was larger than all other angle errors.

Manual tracking did not appear to facilitate or hinder gaze tracking though some gaze errors were slightly smaller in the gaze only condition compared to the gaze in the manual condition.

2.3.6.5 Gaze tracking in the manual condition: The effect of repetition (attempt no.) on the in-line component of tracking

Total position errors ($F(2,18)=24.113$, $p<.001$) were significantly affected by tracking attempt. Contrasts revealed a significant difference from the first to the second attempt ($F(1,9)=28.299$, $p<.001$).

Tracking was always behind the target though the distance behind was reduced significantly from first to second attempt ($p<.001$) (Figure 2-57). No reduction in the error mean was seen at the third attempt. These errors match almost exactly those of the gaze only condition and do not resemble, in value or change in value, those in the manual tracking condition.

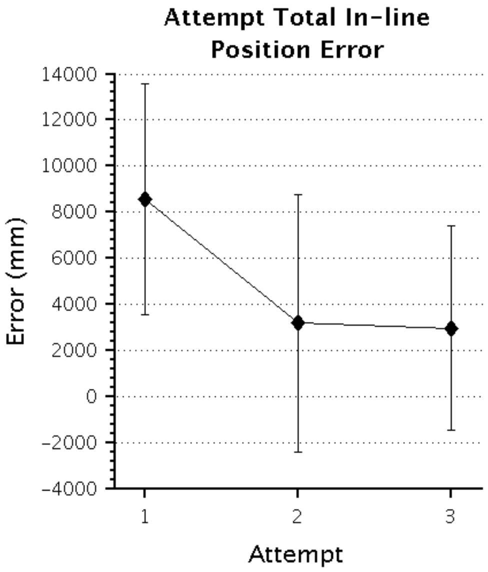


Figure 2-57. Gaze tracking (in the manual condition) mean total position errors (with SD) along the line of target motion for the effect of repetition (attempt).

Section Summary

Tracking position errors did decrease with practice but never achieved a near zero nor did they ever move ahead of the target, as was the case when manual tracking. However, as with angle data, these data are similar to the gaze only condition.

2.3.6.6 Gaze tracking in the manual condition: Angle-attempt interaction on the in-line component of tracking

No significances were found in angle attempt interactions though the pattern or error is nonetheless informative.

The pattern of error in interaction in-line total position data (Figure 2-58) is very similar to that of angle error in the same measure (Figure 2-55). As suggested by the attempt errors (Results 2.3.6.5) there is a reduction first attempt to the second attempt and smaller reduction from the second attempt to the third attempt. The reduction in error with practice is larger in this condition than it was in the gaze only condition but this appears to be because of larger first attempt errors when tracking at angles <45° as error ≥45° are similar in both conditions.

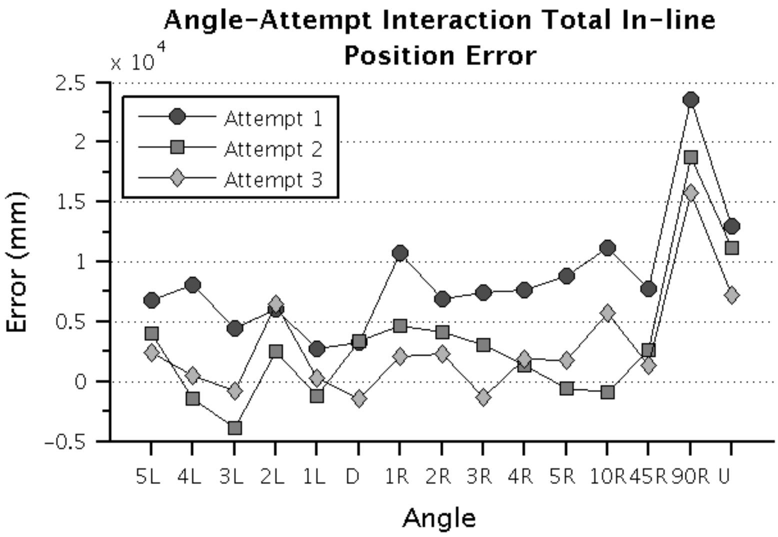


Figure 2-58. Gaze tracking (in the manual condition) mean total position errors along the line of target motion for different directions (angles) and the effect of repetition (attempt).

Section Summary

No significant differences were found, and the data is extremely similar in pattern and values to the gaze only data.

2.3.6.7 Gaze tracking in the manual condition: The effect of target angle on the sideways component of tracking

Total position error was significantly affected by the target path angle (uncorrected $F(14,126)=4.399$, $p<.001$; GG $F(2.87,25.833)=4.399$, $p=.013$; HF $F(4.256,39.207)=4.399$, $p=.004$). Contrasts revealed vertically down to be significantly different to 90° right ($F(1,9)=11.351$, $p=.008$).

Tracking was left of the target (negative error) and equal for all angles apart from 90° right, during which it was much further left (real world downwards) and vertically up when tracking was to the right of the (counter-rotated) target (positive error) (Figure 2-59) i.e. again to the left of the target in real world terms. The pattern and values are almost identical to that in the gaze only condition. However the value of 90° right error is here slightly larger and the vertically up tracking error is slightly smaller.

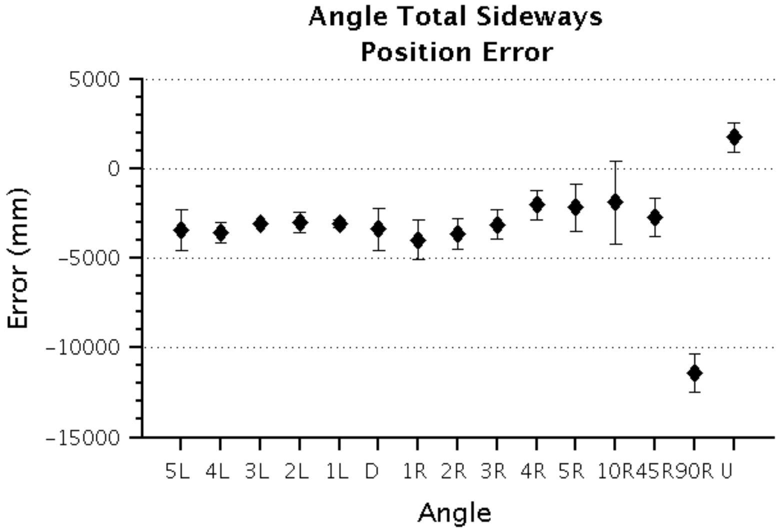


Figure 2-59. Gaze tracking (in the manual condition) mean total position errors (with SD) perpendicular to the line of target motion for different directions (angles).

Total velocity error was significantly affected by the target path angle (uncorrected $F(14,126)=13.918$, $p<.001$; GG $F(5.221,46.991)=13.918$, $p<.001$; HF $F(13.288,119.592)=13.918$, $p<.001$). Contrasts revealed vertically down to be significantly different to: 5° right ($F(1,9)=12.934$, $p=.006$); 10° right ($F(1,9)=19.623$, $p=.002$); 45° right ($F(1,9)=18.947$, $p=.002$); and 90° right error ($F(1,9)=30.597$, $p=.000$).

Gaze tracking velocity errors were all positive (greater rightwards velocity than the target) with the exception of 2° left which was slightly negative (greater leftwards velocity that the target) and 90° right which was negative (real world downwards) and the second largest error (Figure 2-60). Leftwards angles tended to be roughly equal to the error seen for vertically down, but errors for the rightwards angular deviations from vertical increased as the angular deviation increased.

The pattern and values are very similar to those in the gaze only condition (Figure 2-48). However in that condition the leftwards angles tended to have negative error (indicating greater leftwards velocity than the target) whereas here this was not the case.

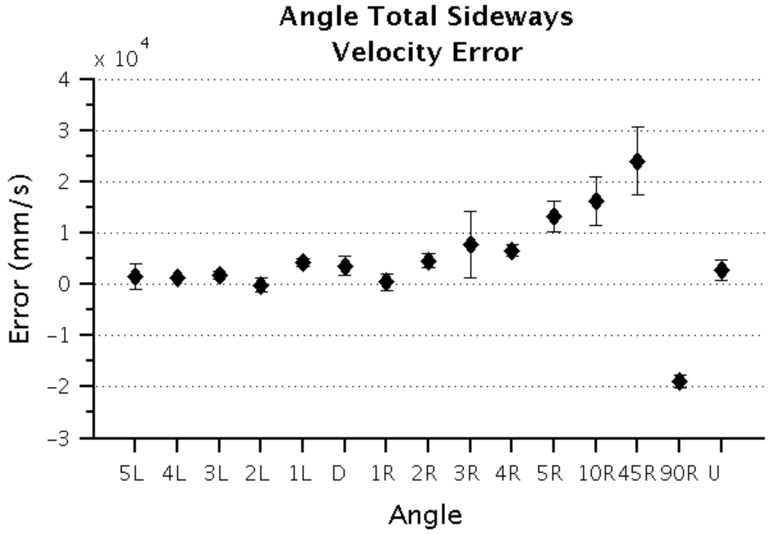


Figure 2-60. Gaze tracking (in the manual condition) mean total velocity errors (with SD) perpendicular to the line of target motion for different directions (angles).

Total acceleration error was significantly affected by the target path angle (uncorrected $F(14,126)=3.495$, $p<.001$; GG $F(4.299,38,691)=3.495$, $p=.014$; HF $F(8.719,78.475)=3.495$, $p=.001$). Contrasts revealed vertically down to be significantly different to 5° left ($F(1, 9)=7.175$, $p=.025$); 45° ($F(1,9)=11.085$, $p=.009$).

There is no pattern (Figure 2-61) though this data resembles that of the gaze only condition and bears no resemblance the clear positive gradient seen in the errors for the pointing arm during manual tracking.

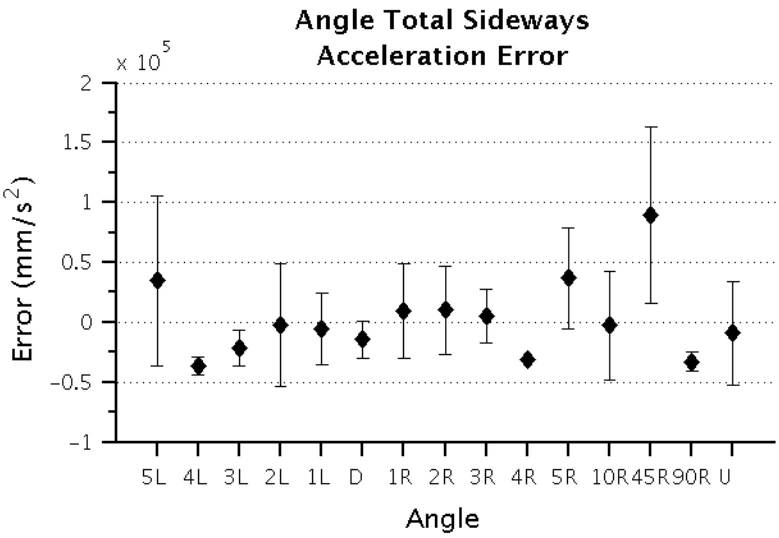


Figure 2-61. Gaze tracking (in the manual condition) mean total acceleration errors (with SD) perpendicular to the line of target motion for different directions (angles).

Section Summary

As with the in-line error these sideways errors show a very close resemblance to the gaze only tracking. This supports the previous assertion that gaze tracking is independent of manual tracking. This cannot be a result of experimenter effects (participants focussing on manual tracking believing that is the important measure being recording) because of almost perfectly matching results in the gaze only condition and, for the same reason, it cannot be an effect of visual or motor processing interference from the dual task (gaze AND manual).

2.3.6.8 Gaze tracking in the manual condition: Angle-attempt interaction on the sideways component of tracking

For total position error results show no significant interaction between the angle condition and the number of the attempts made. As would be expected from the angle data SD and the attempt mean errors, there is little difference between the attempt means within angles. The pattern of data is similar to that seen in the angle data.

Error means for angles <90º and for vertically up are typically slightly lower than those in the gaze only condition and whilst for 90º they are slightly higher (Figure 2-62).

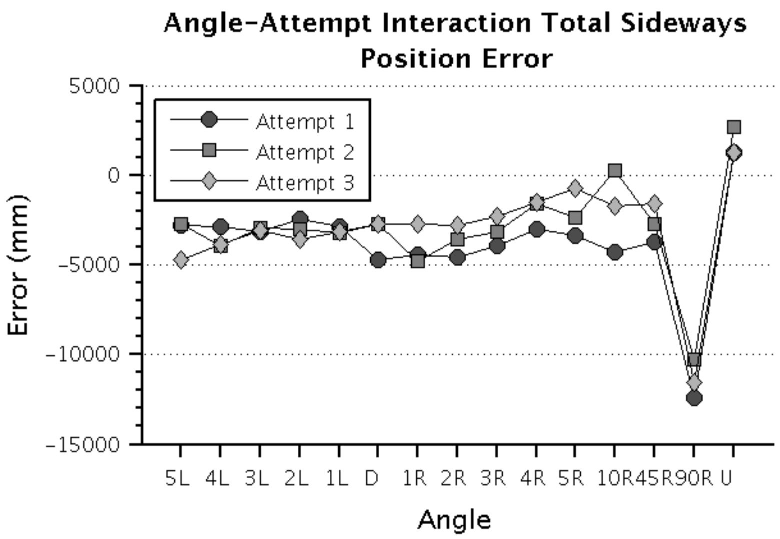


Figure 2-62. Gaze tracking (in the manual condition) mean total position errors perpendicular to the line of target motion for different directions (angles) and the effect of repetition (attempt).

For total velocity error the results show that may have been a significant interaction between the angle condition and the number of the attempts made (uncorrected $F(28,252)=1.404$, $p=.092$; GG $F(4.878,43.899)=1.404$, $p=.243$; HF $F(11.347,102.126)=1.404$, $p=.18$). Contrasts revealed a significant difference between the second attempt and the third for 1° right ($F(1,9)=4.833$, $p=.055$).

Little difference in the leftwards angles though tended to be positive and become less with practise meaning less rightwards movements (Figure 2-63). Rightwards angles tended be positive and increase meaning more rightwards movement. Further rightwards angles errors increase as angle increased up and including 45° right. The error when tracking vertically upwards was roughly equal to that when tracking vertically downwards. Error when tracking 90° right was negative and became increasingly negative meaning increasing leftwards movement.

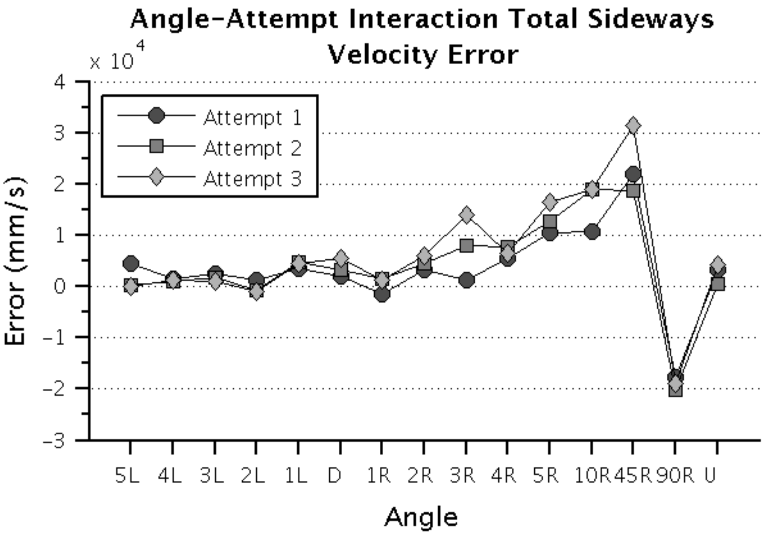


Figure 2-63. Gaze tracking (in the manual condition) mean total velocity errors perpendicular to the line of target motion for different directions (angles) and the effect of repetition (attempt).

Section Summary

As expected from angle and attempt data there was little difference between attempts at every angle. Interestingly the difference between left and right shallow angles (i.e. ≤5º) is clearer in the interaction data than it was in angle data.

2.3.7 Gaze tracking in the laser condition

2.3.7.1 Gaze tracking in the laser condition along the direction of target movement time series plots

These plots (Figure 2-64) show several features common to all tracking attempts:

- There is an intial reaction of 100-150 ms where gaze is stationary – there is zero tracked velocity and acceleration.
- Following this appears to be a short period of smooth pusuit shown as smooth curve in the velocity profile before a first saccade at ~250-300 ms.
- The first saccade is seen as a steep change in velocity but also an acceleration pulse.
- There appears to be a second saccade at 550-600 ms which again shows a change in velocity and an acceleration pulse.
- Between the two clear saccades at ~450-550 ms there may be a period of smooth pursuit but the turbulent velocity profile may indicate the averaging of saccades that are not synchronised in time.

As with in the other gaze tracking time series, in this tracking condition there appears to be two saccades though they are more muted than in those other conditions. Error was further behind the target than in the other gaze conditions and the laser condition

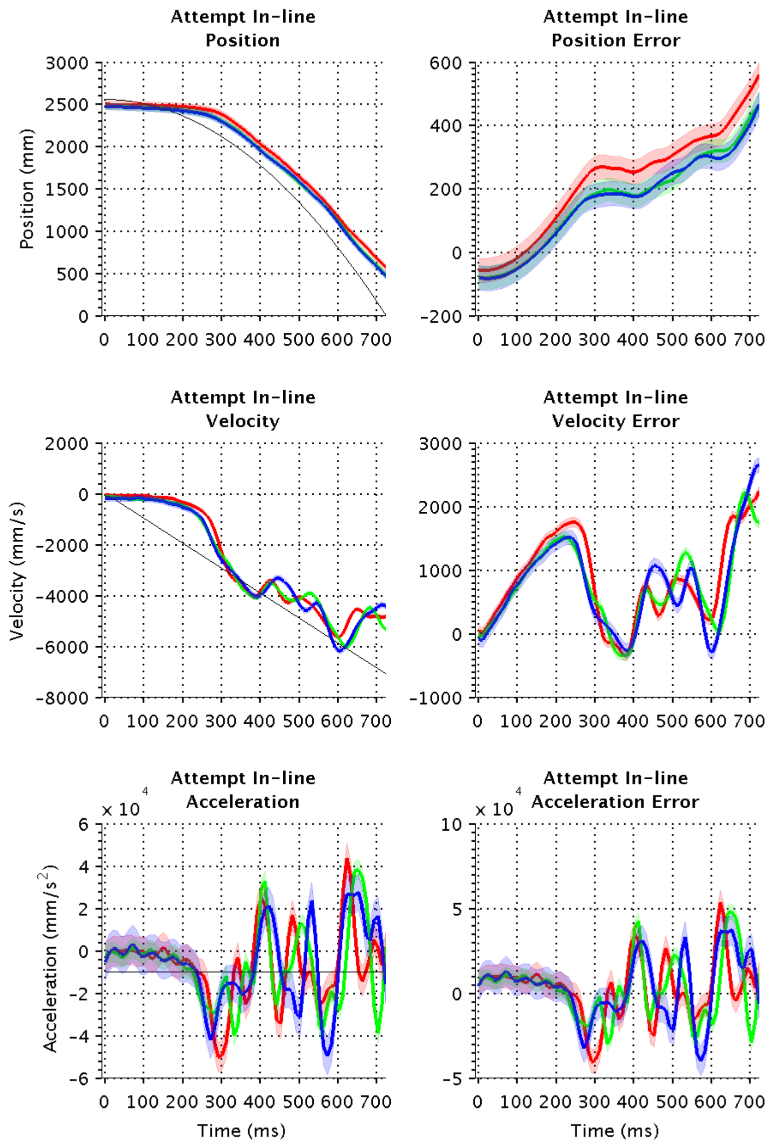


Figure 2-64. Time series of gaze tracked (in the laser condition) in-line position, velocity and acceleration for each attempt. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

2.3.7.2 Gaze tracking in the laser condition: Trajectory plots

See Results 2.3.3.2 for a description of the plot components.

The features of tracked trajectory in this condition are indistinguishable to those in the gaze only condition (Results 2.3.5.2).

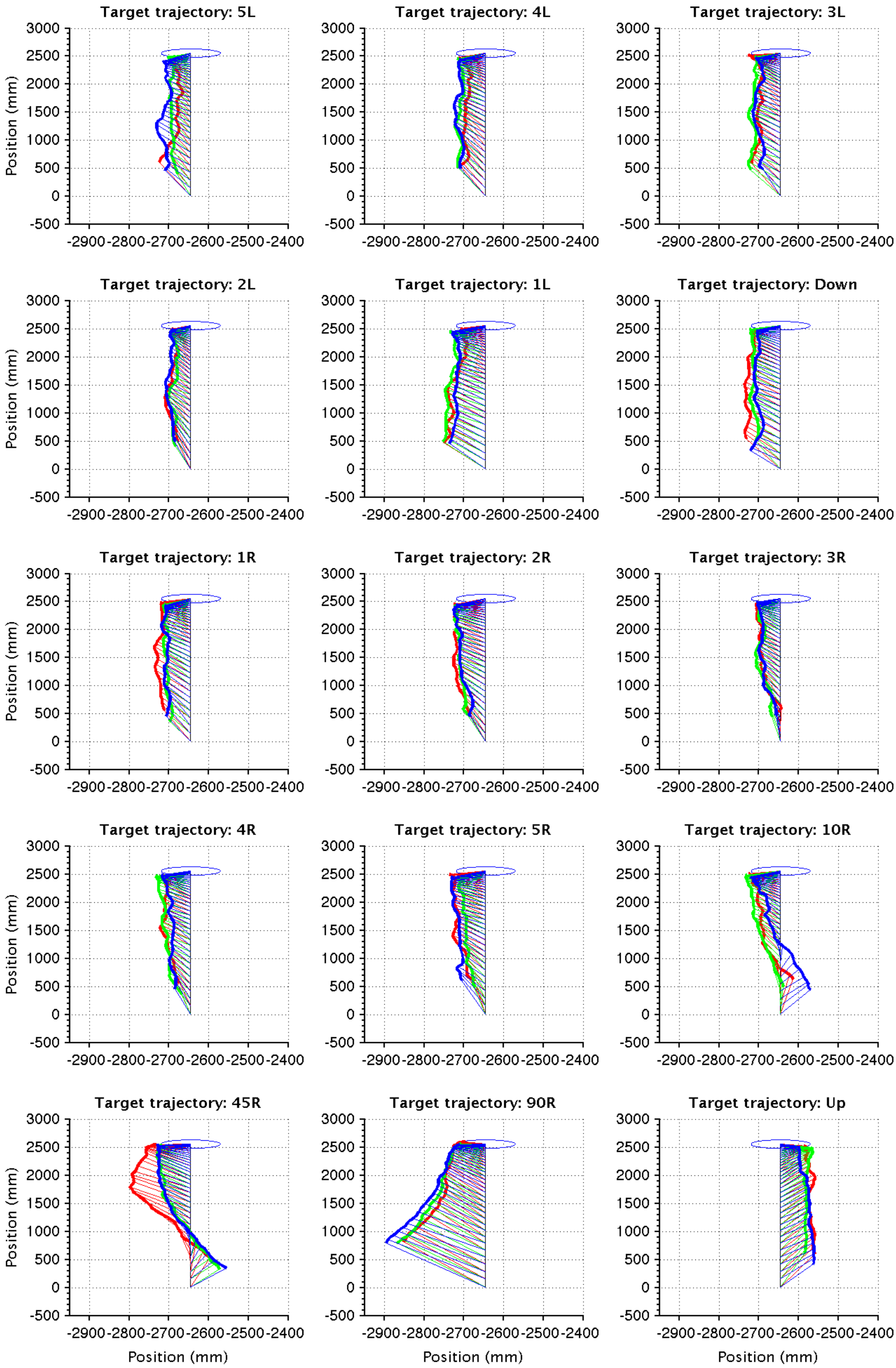


Figure 2-65. Trajectory plots of gaze tracking (in the laser condition) in each angle condition. Thick red, green and blue lines are the mean first, second and third tracking attempts and the thin black is the target's trajectory. Lines joining tracked trajectory to target trajectory are indicate position at every odd sample number.

2.3.7.3 Gaze tracking in the laser condition: Time series of tracked position error for individual target directions

Along the direction of target movement (in-line)

At leftwards angles, rightwards angles <45º and the vertical trajectories tracking at 1 ms was ~100 mm ahead of the target (negative error) and fell increasingly behind over the course of target movement to ~500 mm behind the target (positive error) at 730 ms (Figure 2-66). For these angles there are two saccades that are at approximately the same time (~300 ms and ~500-600 ms) though they are and less pronounced and reduce error less than saccades in the other gaze conditions (gaze only condition [Results 2.3.5] and gaze in the manual condition [Results 2.3.6]). The error in this condition for these is generally larger and larger at the end of tracking.

In the other gaze conditions tracking at 45º yielded lower errors than in this condition. Also, the gradient for tracking at 90º is much steeper than at the other angles. This was expected following the larger errors in the angle (Results 2.3.7.4) and attempt data (Results 2.3.7.5) that showed poorer gaze tracking when tracking with the laser.

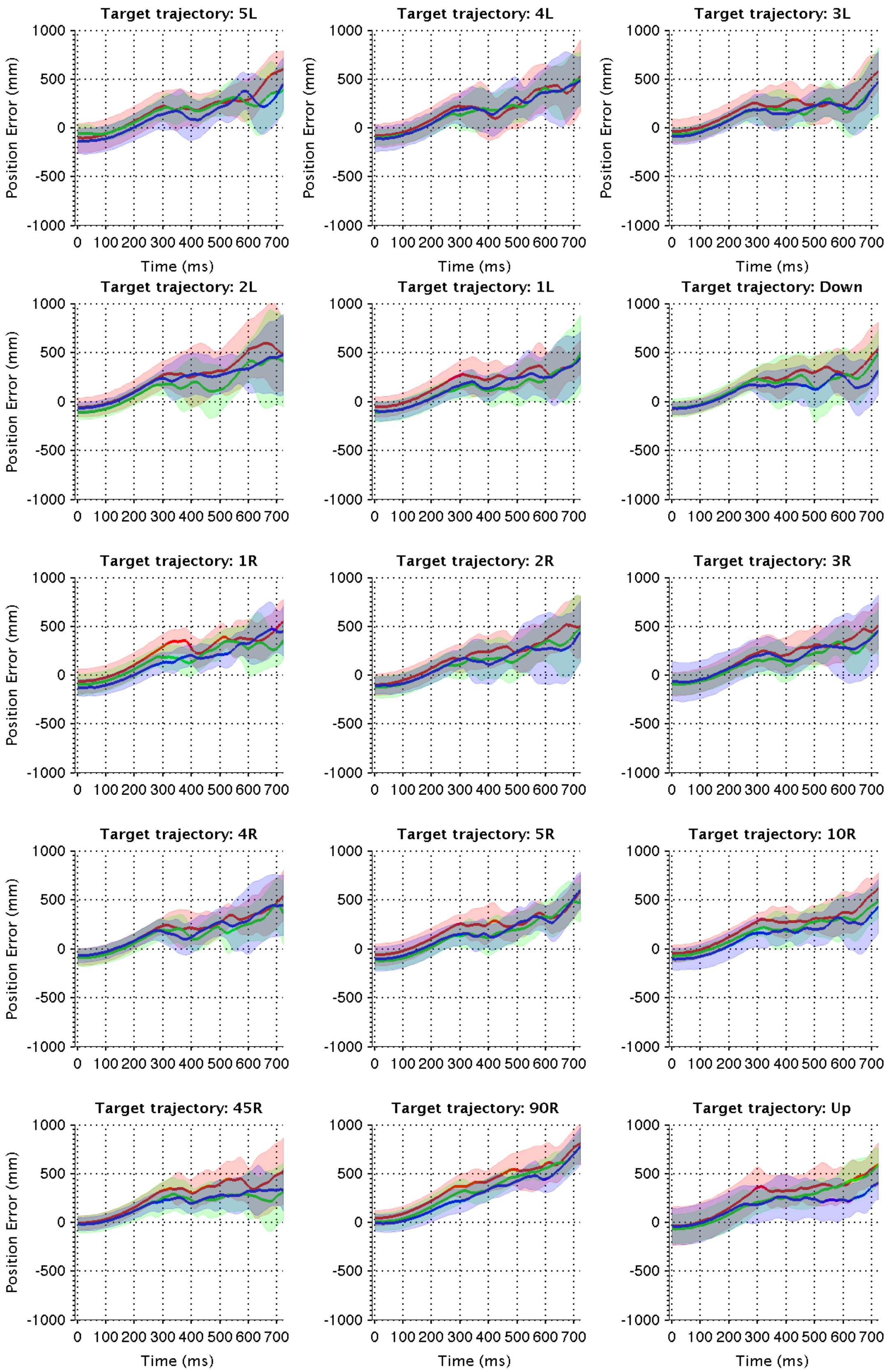


Figure 2-66. Time series of gaze tracked (in the laser condition) in-line position error for each angle condition. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

Perpendicular to the direction of target movement (sideways)

Errors at 1 ms (the starting error) was typically between approx. -50 and -100 mm for all angles apart from vertically up for which the error was of the same magnitude but positive (Figure 2-67). This was also found in the other gaze tracking conditions, though there was little offset when tracking vertically upwards in the gaze and manual conditional. I have previously suggested that the consistency of the offset and the reversal of sign when tracking vertically up were indicative of a methodological error rather than a behavioural phenomenon.

For rightwards angles >2º there is a slight positive gradient to the error which indicates that tracking was moving to the right. There is no such pattern when tracking leftwards apart from a negative gradient at 1º indicating tracking moving leftwards. There are steep positive gradients to error when tracking at 10º and 45º right and a steep negative gradient when tracking at 90º right. The absolute change in error from 1 ms to 730 ms for these angles is approximately 150 mm.

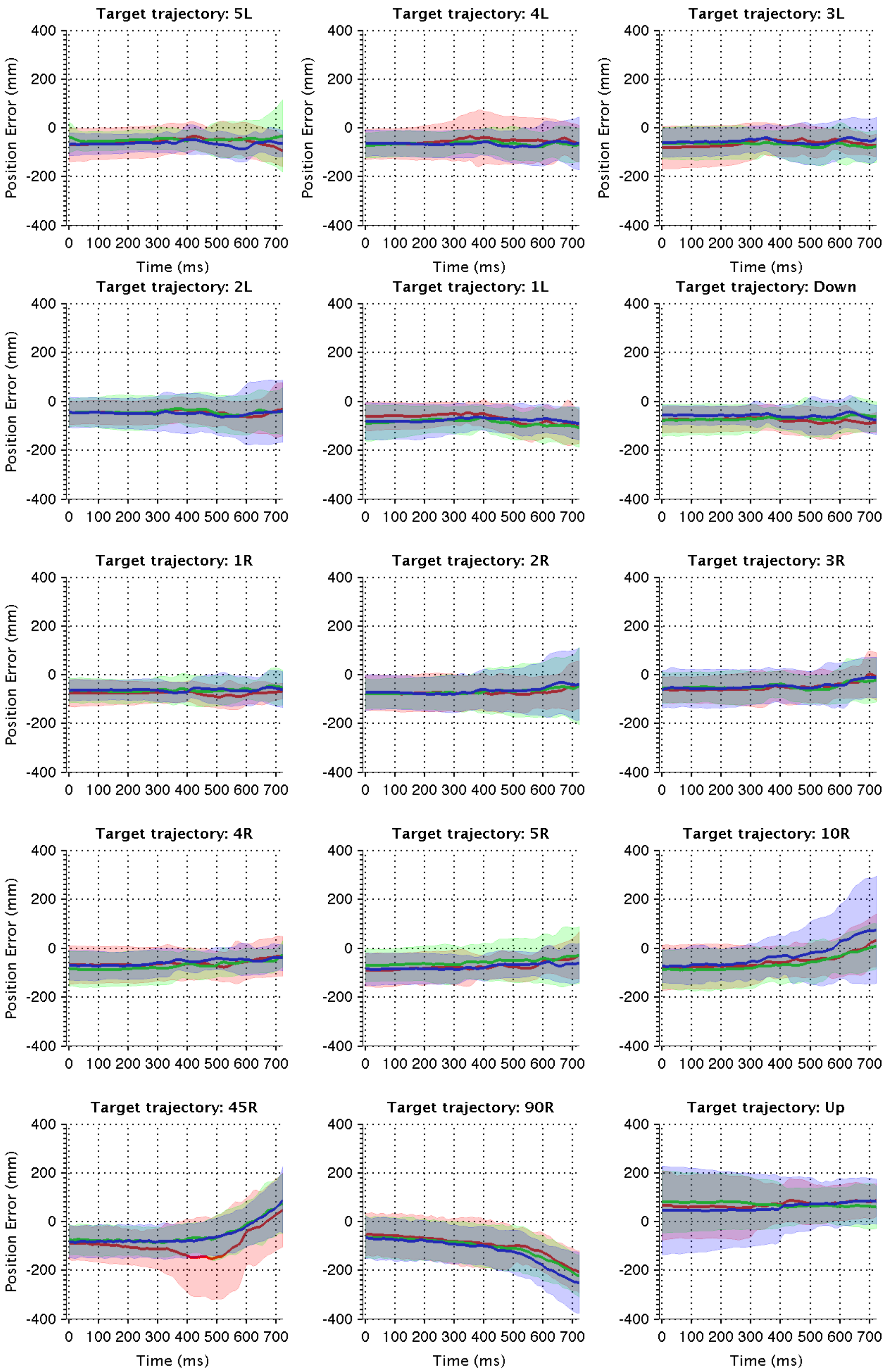


Figure 2-67. Time series of gaze tracked (in the laser condition) sideways position error for each angle condition. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

2.3.7.4 Gaze tracking in the laser condition: The effect of target angle on the in-line component of tracking

Total position error was significantly affected by the target path angle (uncorrected $F(14,140)=5.27$, $p<.001$; GG $F(4.464,44,644)=5.27$, $p=.001$; HF $F(8.51,85.102)=5.27$, $p<.001$). Contrasts revealed vertically down to be significantly different to 90° right ($F(1,10)=22.418$, $p=.001$). Contrasts approaching significance were between 45° right ($F(1,10)=4.895$, $p=.051$).

Tracking was always behind the target (positive error) and did not vary until angles were >10° whereupon the errors increased (Figure 2-68). Tracking at 45° right and vertically up was slightly further behind the shallower angles though only tracking at 90° right was significantly further behind than vertically down ($p=.001$).

Compared to the gaze only condition (Figure 2-43), errors in this condition were approx. 1000 mm greater at every angle apart from at 90º where the error was only slightly greater though the pattern of error was similar. However it is interesting that for all angle errors apart from 90º and vertically up the gaze error is approx. 400 mm greater than the laser error in the same condition, and that this is around the typical error for those angles in the gaze only condition.

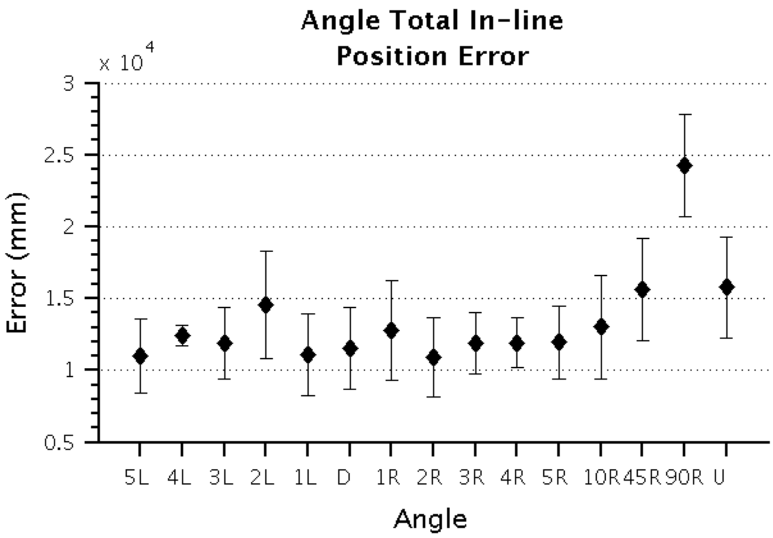


Figure 2-68. Gaze tracking (in the laser condition) mean total position errors (with SD) along the line of target motion for different directions (angles).

Total velocity error may have been significantly affected by the target path angle (uncorrected $F(14,140)=2.242$, $p=.009$; GG $F(4.698,46.977)=2.242$, $p=.069$; HF $F(9.369,93.686)=2.242$, $p=.024$). Contrasts revealed vertically down to be significantly different to 90° right ($F(1,10)=13.008$, $p=.005$).

All tracking was slower than the target (negative error) and varied little apart from when tracking 45° right for which the error was slightly smaller and when tracking 90° right for which the error was significantly larger (further behind) than vertically down (p=.005) (Figure 2-69).

At vertically up and from 5° left to 10° right these errors are approximately twice those of the gaze only condition. The error at 45° right and 90° is closely matched the gaze only condition. The errors in the laser condition are not as closely matched as they were for the total position measure. They are consistently around 2x104 m/s^2 (2000 mm/s^2) faster than these errors.

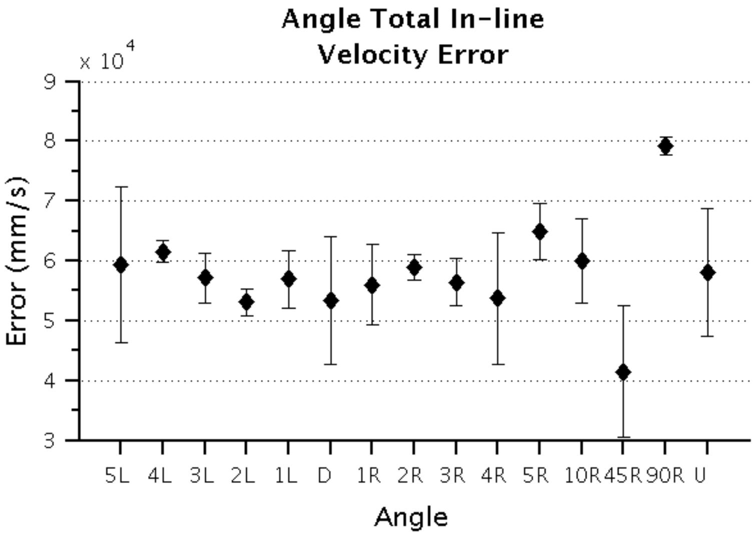


Figure 2-69. Gaze tracking (in the laser condition) mean total velocity errors (with SD) along the line of target motion for different directions (angles).

Section Summary

The gaze tracking errors in the laser condition were larger than in any other tracking method condition, for all angles tested at each measure.

In Discussion I argue that the distance by which gaze tracking was behind the target was roughly the same in the manual and dedicated gaze condition, suggesting that gaze was not radically affected by simultaneously performing another task and that gaze was tracking the same stimulus in both conditions (i.e. the target and not where the participant believed they were pointing). However, gaze tracking in the laser condition was further behind gaze in the other conditions and was more homogenised between mean angle errors. Laser tracking was also homogenised and was behind the target. Also, gaze tracking in the laser condition was behind laser tracking in the same condition by roughly the same amount that gaze tracking in the gaze only and the gaze and manual condition was behind the target (Discussion 2.4.9.1). I also argue that gaze in the laser condition was following the laser spot rather than the target.

2.3.7.5 Gaze tracking in the laser condition: The effect of repetition (attempt no.) on the in-line component of tracking

Total position errors ($F(2,20)=50.205$, $p<.001$) were significantly affected by tracking attempt. Contrasts revealed a significant difference from the first to the second attempt ($F(1,10)=89.264$, $p<.001$).

Tracking remained behind the target even after a significant improvement ($p<.001$) in tracking error from first to second attempt (Figure 2-70). There was no improvement at the third attempt. In the gaze only condition the mean error was smaller at each attempt (~.9x104 mm (~9000 mm)) than in this condition though the amount of improvement was roughly equal (a reduction of ~4.5x104 mm (~4500 mm) from first to third attempt). The first attempt error in this condition is only slightly larger than the first attempt error for laser tracking though there is less reduction in angle error.

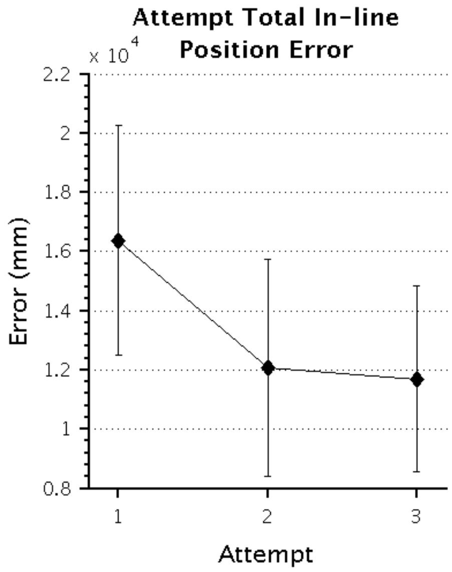


Figure 2-70. Gaze tracking (in the laser condition) mean total position errors (with SD) along the line of target motion for the effect of repetition (attempt).

Section Summary

As with the angle errors, the laser tracking errors were smaller than the gaze tracking errors in the laser condition. However unlike the angle errors there was not a clear relationship between the gaze and laser errors. This is probably because of the averaging of angle errors into each attempt.

2.3.7.6 Gaze tracking in the laser condition: Angle-attempt interaction on the in-line component of tracking

For total position error results show that there was no significant interaction between the angle condition and the number of the attempts made (uncorrected $F(28,280)=.821$, $p=.728$; GG $F(5.267,11.817)=.821$, $p=.545$; HF $F(11.817,118.171)=.821$, $p=.627$).

Tracking was behind the target (positive error) for all attempts at every angle but the distance behind was reduced by second and third attempt for every angle condition (Figure 2-71). This has not been clear in the gaze conditions. There was no significant difference in the amount of improvement between attempts for angles compared to vertically down.

The error at each number of attempt was roughly equal for all angles <45° and at these angle the improvement from one attempt to the next was roughly equal. Tracking targets moving 45° right and vertically up yielded errors that there were slightly larger than the shallower angles whilst errors at 90° right were much larger but the reduction in error with practice was similar to the shallow angles for these angles.

The pattern of errors is similar to that in the gaze only condition though the errors are larger. At angles <45° the errors are approx. 10,000 mm larger and at other angles are approx. 5000 mm larger than in the gaze only condition. Interestingly the first attempt errors at angles <45° were similar to laser tracking errors but failed to reduce as much with practice. The errors at 90° right and vertically up were not similar.

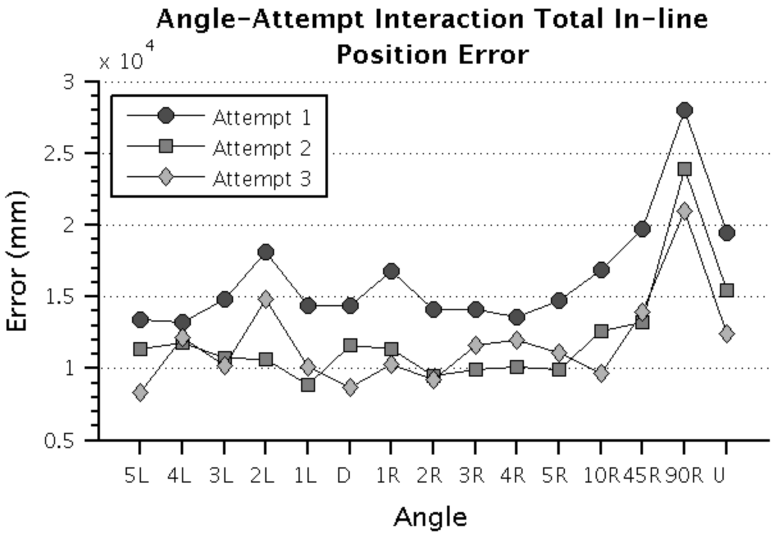


Figure 2-71. Gaze tracking (in the laser condition) mean total position errors along the line of target motion for different directions (angles) and the effect of repetition (attempt).

Section Summary

All errors were positive meaning that at each attempt in each angle tracking was behind the target. The distance behind was greater than gaze tracking in the gaze only condition and laser tracking which had the largest non-gaze errors. Although the mean errors matched more closely the mean errors of laser tracking, they were most similar in pattern to the gaze only condition because of the very large and unchanging errors when tracking 90° rightwards and the generally low errors when tracking vertically upwards.

The errors go some way to support the previous assertion that tracking was following the laser spot rather than the target (see Section Summary for Results 2.3.7.4 and Discussion 2.4.9.1).

2.3.7.7 Gaze tracking in the laser condition: The effect of target angle on the sideways component of tracking

Total position error was significantly affected by the target path angle (uncorrected $F(14,126)=6.233$, $p<.001$; GG $F(2.721,27.305)=6.233$, $p=.003$; HF $F(3.836,38.363)=6.233$, $p=.001$). Contrasts revealed vertically down to be significantly different to vertically up ($F(1,10)=15.770$, $p=.003$).

All angles were tracked to the left of the target (negative error) by roughly the same amount apart from vertically up which was tracked to the right (positive error) by that roughly amount (Figure 2-72). Tracking at 90° right resulted in slightly more leftwards tracking (real-world downwards) than the other angles.

This data is extremely similar in pattern and value to that in the gaze only condition and bears little resemblance to the laser tracking.

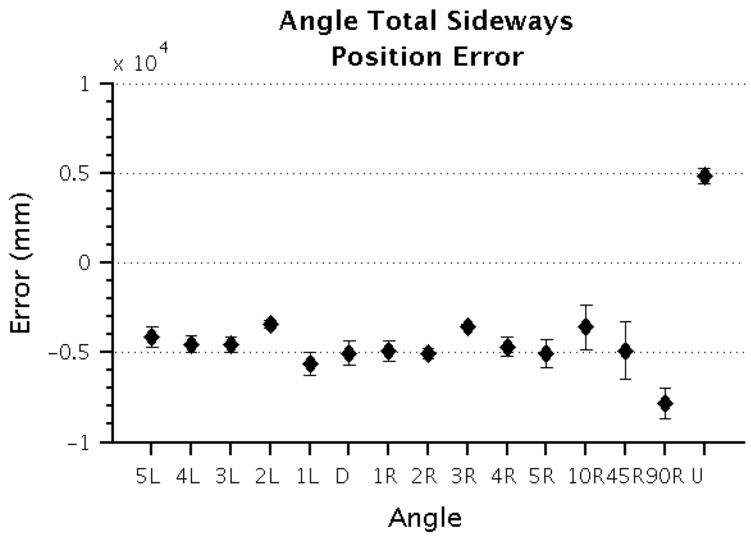


Figure 2-72. Gaze tracking (in the laser condition) mean total position errors (with SD) perpendicular to the line of target motion for different directions (angles).

Total velocity error was significantly affected by the target path angle (uncorrected $F(14,126)=11.22$, $p<.001$; GG $F(3.853,38.529)=11.22$, $p<.001$; HF

$F(6.569,65.691)=11.22$, $p<.001$). Contrasts revealed vertically down to be significantly different to: 3° right ($F(1,10)=8,959$, $p=.013$); 4° right ($F(1,10)=7.915$, $p=.018$); 5° right ($F(1,10)=6.737$, $p=.027$); 10° right ($F(1,10)=30.331$, $p<.001$); 45° right ($F(1,10)=18.833$, $p=.001$); and 90° right ($F(1,10)=32.329$, $p<.001$).

Tracking targets moving rightwards with a downwards component resulted in positive errors (meaning the tracking velocity was overall greater than the target velocity) and this error typically increased as the angular deviation away from vertically down increased (Figure 2-73). Tracking of leftwards moving targets varied little and was roughly equal to the vertical trajectory errors that were amongst the lowest. However from 5° left to 2° left there is a slight positive gradient suggesting a shift from leftwards to rightwards tracking as the angle decreased.

This data again is very similar to the gaze tracking in the gaze condition but dissimilar to the laser tracking.

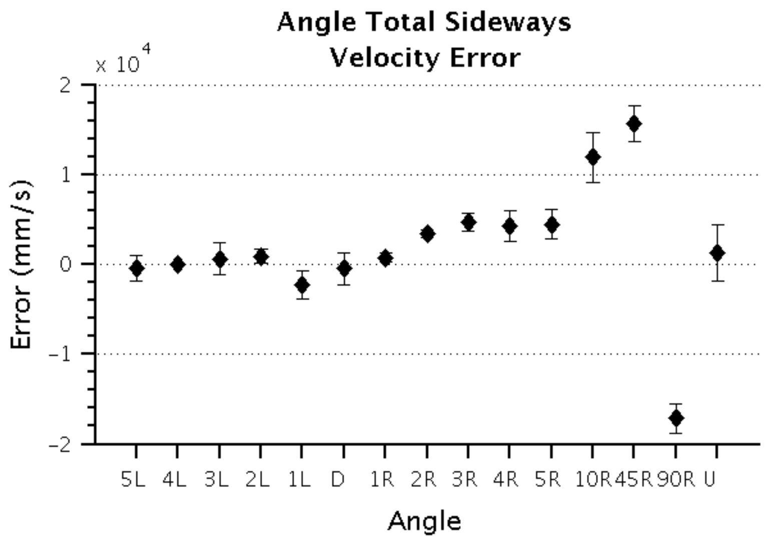


Figure 2-73. Gaze tracking (in the laser condition) mean total velocity errors (with SD) perpendicular to the line of target motion for different directions (angles).

Total acceleration error was significantly affected by the target path angle (uncorrected $F(14,126)=2.236$, $p=.009$; GG $F(4.984,49.843)=2.236$, $p=.065$; HF $F(10.533,105.326)=2.236$, $p=.019$). Contrasts revealed vertically down to be significantly different to 45° right ($F(1,10)=7.747$, $p=.021$) and 90° right ($F(1,10)=7.921$, $p=.018$).

There is little clear pattern though the distribution of errors resembles that in the position and velocity errors (but with less difference to the errors at 45° right and 90° right) (Figure 2-74). Errors at all angles were roughly equal apart from at 45° right (large positive error) and 90° right (large negative error). In the laser tracking there was a positive gradient and smaller errors.

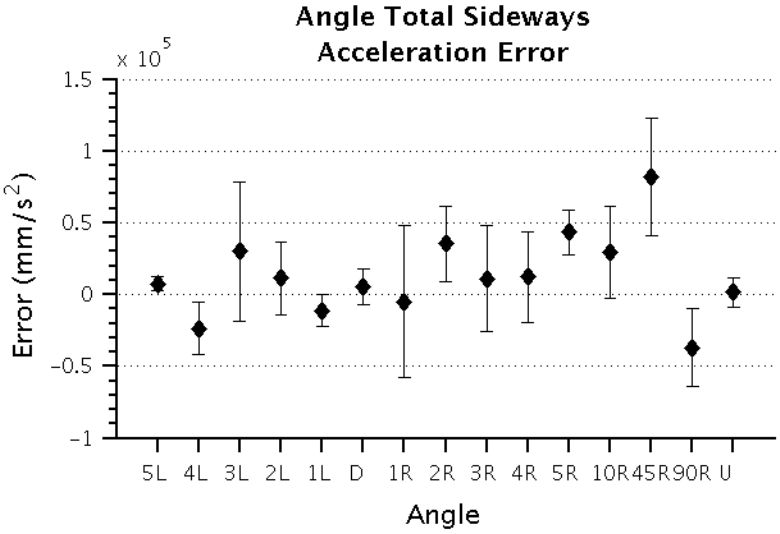


Figure 2-74. Gaze tracking (in the laser condition) mean total acceleration errors (with SD) perpendicular to the line of target motion for different directions (angles).

Section Summary

These errors suggest that tracking was more similar to gaze tracking the gaze only condition than it was to laser tracking (the same condition in which this gaze data was collected). This is in contrast to the in-line where although the pattern was most similar to gaze tracking errors in the gaze only condition, the values were typically closer to the laser tracking errors. It may be that only the parallel component of tracking was influenced by the laser spot feedback.

2.3.7.8 Gaze tracking in the laser condition: Angle-attempt interaction on the sideways component of tracking

There was no within angle pattern (i.e. no attempt error change) and the angle pattern for both total sideways position errors (Figure 2-75) were matched those in the angle data (Results 2.3.7.7).

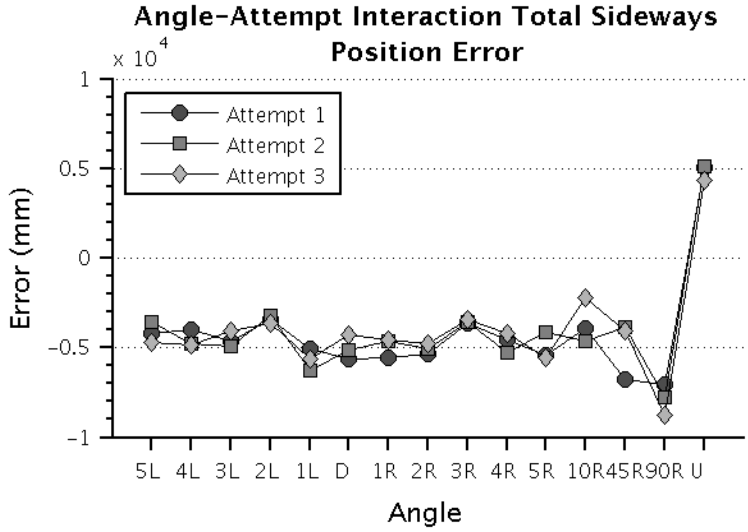


Figure 2-75. Gaze tracking (in the laser condition) mean total position errors perpendicular to the line of target motion for different directions (angles) and the effect of repetition (attempt).

2.4 Discussion

2.4.1 Main questions and general findings

In the discussions that follow I present evidence in favour of a directionally tuned internal model of gravity and evidence that pointing, from the actor's perspective, is judged by a vector from the dominant eye, past the finger and onto the target. I now briefly outline several important features that will be examined in greater detail in following Discussion sections.

1. The method of tracking and the target's trajectory had highly significant effects ($p<.001$) on tracking output so each tracking method was examined separately. Within each method, I examined tracking differences across target trajectories, between attempts and any interactions between these two.
2. Tracking by finger pointing was achieved using a vector from the dominant eye past the pointing fingertip and onto the target.
3. Gaze tracking in isolation did not differ from gaze tracking with addition of the manual pointing, but did differ from gaze tracking with the addition of the laser pointing.
4. Manual tracking of targets moving at 1° from the vertical was towards the vertical. Manual tracking was always ahead of the target, so tracking towards the vertical might indicate an expectation of a parabolic trajectory as would naturally occur, with instantaneous direction tending towards vertically down with time.

5. Tracking at 2-10° was typically similar suggesting that tracking control may be broadly tuned.
6. The tracking of an ascending target was always the worst. The pattern of errors suggests that there was an assumption that targets would no accelerate upwards.
7. Tracking of horizontally moving targets was always very poor. There might be an assumption of constant horizontal velocity just like something rolling along a surface.
8. 45° tracking was typically parabolic – as though the target was expected to follow a natural trajectory
9. The laser provided accurate feedback that prompts (or pushes the control mode into) reliance on feedback rather than prediction

2.4.2 Mode of manual tracking

The main finding is that the vector from the dominant eye to the pointing index finger tip is the vector used by participants to manually track the target.

Tracking errors for the left eye to fingertip vector were larger than those using the right eye to fingertip vector, and the errors calculated from the dominant eye were similar to, though smaller than, those from the right eye. This is because 'line of sight' is strongly influenced by eye dominance, and right eye dominance was more common (62.5%, n=16). It is possible to observe the effect of eye dominance on the choice of location of the fingertip if one looks at and points at a target with both eyes open then closes each eye in turn. Closing the non-dominant eye has no effect whereas closing the dominant eye changes 'line of sight' and introduces a pointing mismatch error.

Though it appeared from observations that participants were looking past their index finger tip, they may have instead been looking down the length of the extended finger. If this were the case then the eye to finger tip vector should be similar to the middle or base knuckle to finger tip vector, whereas if participants looked past the finger tip itself then one would expect a negative position error for the former and a positive position error for the latter. The latter is the case meaning that one looks past the fingertip when pointing at a target.

Of all the vectors investigated, the vector from the dominant eye through the fingertip to the screen yielded the lowest means and standard deviations for the total tracking error, which suggests that this is the vector actually used by participants to track the target. This work represents, to the author's knowledge, the first systematic investigation into the natural way of accurately pointing to a target location.

2.4.3 Main effects on tracking output

In this experiment I used the output of controlled motion under different conditions to investigate directional aspects of a possible internal model of gravity. I first executed a full-factor ANOVA on all data looking for main-effects of target trajectory, tracking method and repetition before then breaking down effects with one-way ANOVAs and 2-way repeated-measures ANOVAs to identify differences between trajectories and tracking methods, and between trajectories and repetitions within each tracking condition.

Target trajectory was found to significantly affect ($p<.001$) tracking output when all tracking methods were grouped together. Tracking horizontally and vertically upwards yielded significantly greater errors than for other directions ($p<.001$). This means that participants were better at tracking predictable naturally moving targets (accelerating in some downwards direction) than predictable unnaturally moving targets (accelerating upwards or horizontally) – an indication of an internal model of gravity.

Participants executed visually guided tracking of the target in three main ways: pointing a finger; pointing a laser; or gaze tracking. These are fundamentally different methods because manual and laser tracking require movement of the arm that is subject to mechanical, inertial and gravitational forces, whereas movement of the eye is largely free from such forces. Further the judgement of tracked position is different for all three main methods in that manual tracking requires the participant make a subjective judgement of their tracked position whereas when laser tracking, the tracking output (laser spot) is clear and immediate and when gaze tracking the target should simply be the focal point of attention. Though the required tracking output was the same for each tracking condition, I found that the actual output differed highly significantly ($p<.001$) between the three main tracking conditions of manual tracking, laser tracking and all pooled gaze tracking (see Results 2.3.2). Also, gaze tracking in isolation and gaze tracking in the manual condition were found to differ highly significantly ($p<.001$) from gaze tracking in the laser condition but not from each other. This suggests that gaze tracking was controlled in the same way for both gaze tracking in isolation and in the manual condition (see Discussion 2.3.6).

As a result of the identified differences in tracking I analysed manual, laser and all gaze tracking methods separately.

2.4.4 Gravitational and inertial effects on movement

Gravity (as a persistent downwards force) may facilitate manual and laser tracking of descending targets. Conversely, gravity would hinder manual and laser tracking of ascending targets and potentially hinder tracking of targets with any horizontal motion. There is, however, evidence that gravitational influence on movement is modelled. Virji-Babul, Cooke, & Brown (1994) found elbow flexion/extension movements made with or against gravity show similar velocity profiles, peak velocities and movement durations but differ in EMG activity; the authors suggest that the CNS takes advantage of known environmental effects when planning movement. Similarly, Gentili et al. (2007) found movements made against gravity were characterised by greater muscle torques than those made with gravity but there was little difference between velocity characteristics; they concluded gravity's mechanical effect on limb movements are modelled. After comparing up/down arm movements in the vertical plane in 1*g* and 0*g* conditions, Papaxanthis, Pozzo, & McIntyre (2005) concluded that the CNS uses internal models of gravity fields and inertial forces when planning and executing arm movements. Furthermore, in arm movements the rapid development of compensatory forces in experimenter imposed force-fields is well document (Davidson & Wolpert, 2003, 2005; Diedrichsen, Hashambhoy, Rane, & Shadmehr, 2005) so extra work should not produce the errors found. Therefore, the direction in which one executes a tracking movement, or the performance when tracking in different directions, is unlikely to be affected by gravitational and load forces. Rather, tracking differences observed in different directions can be ascribed to differences in control.

2.4.5 Manual tracking

2.4.5.1 Manual tracking in-line component

The main findings are that:

- When tracking a descending target (i.e. not 90° right or vertically ascending), the strategy is to track ahead of the target. This is achieved through greater tracking velocity and acceleration than the target.
- When tracking an ascending target, the strategy is to track behind the target. This is achieved with lower tracking velocity and acceleration than the target.
- Tracking errors typically *increase* with practice.

Mean tracked position errors (Figure 2-16 & Figure 2-19) for descending trajectories were negative indicating that tracking was ahead of the target and for ascending targets they were positive indicating that tracking was behind the target (see pull-out section at the back of the thesis). In real world coordinates (i.e. before counter-rotation) both these are below the target. The time series plots (Figure 2-14) show ascending tracking was behind even at the start of tracking (~200 mm behind). All these finding may be a straightforward consequence of the manual tracking method because, in order to judge one's tracking position, one is required to maintain both the finger-tip (as the proximal point of the tracking vector from the eye) and the target in sight. Due to the physical position of the arm/hand/finger relative to the eye one must ensure that the target is above the tracked location to prevent total or partial target occlusion. The starting error for all downwards angle conditions was never more than 100 mm ahead (below) so the greater starting error for upwards target motion, beginning at a different location at the bottom of the screen, was unique to that location and to upwards tracking.

When the target ascends, tracking is slower (Figure 2-17) than when the target descends. As noted, the method of tracking (Discussion 2.4.2) requires that the tracked position remain below the target in real world terms, so it is necessary for descending tracking to be faster than the target, and ascending tracking to be slower. Despite this, there is a large decrease in error from the first attempt to the second and third in ascending tracking (Results 2.3.3.6). This change in error suggests that control, at least following the first attempt, is not based on current visual feedback of target position alone because if it were then there should be no change in tracking output.

The changes in tracking error with practice (Results 2.3.3.5) all exhibited an overall negative gradient, but the sign of the errors at each attempt was not always consistent. Total position error (Figure 2-18) went from being behind the target at the first attempt to ahead by approximately the same amount at the second and third attempts. These changes suggest that at some point during or after the first attempt, the error in tracking was realised and over compensated for, whilst in the second and third attempts tracking was ahead overall – at least for the descending targets (Figure 2-19). The attempt time series plots (Results 2.3.3.1) support this. In these and in the direction time series plots (Results 2.3.3.3), the position error in second and third attempts is similar to that of the first attempt suggesting that the same movement was executed at each attempt but the time of the start of movement was earlier with successive attempts. With practice, the velocity time series show a character increasingly like that of the target. Such a change in movement initiation is reminiscent of a finding in Zago et al. (2004) where, following practice intercepting non-accelerating targets, participants delayed the initiation of a hand movement rather than adjusting their internal model of gravity.

2.4.5.2 Manual tracking sideways component

The main findings are:

- There was a leftwards offset to tracked position.
- When the target trajectory was >1° from the vertical, tracking moved too much to the side that the target was moving but when the trajectory was 1° from the vertical, tracking was towards the vertical.
- Practice at tracking at angles >1° increases error in the direction of target motion whereas at 1° there is little change.
- Tracking of diagonally or horizontally moving targets is affected by an expectation of downwards motion (i.e. prediction of a gravity field).
- There was no clear distribution of errors in the interaction data (Results 2.3.3.8).

Deviations of target movement rightwards away from the vertical by angles greater than 1° yielded total velocity and acceleration errors that indicate tracking was moving increasingly too much to the right of the target, but the total position error showed tracking left of the target (negative). The position measure showed greater negative error for leftwards angles than positive error for the equivalent rightwards angles, but the velocity errors indicate appropriate movement towards the direction of target motion. These features together suggest that tracking was offset to the left. This offset can be clearly seen in the time series (there is no offset from 5° leftwards to 1° rightwards but a negative offset from 2° rightwards onwards).

Velocity errors (Figure 2-21) for leftwards angles >1° were negative, were positive for rightwards angle >1°, and the sign of the error was reversed for leftwards and rightwards angles at 1° (i.e. 1° leftwards positive; 1° rightwards negative). Negative velocities mean that tracking is moving to the left and positive velocities mean that tracking is moving to the right. The same pattern of results was found in the acceleration error. Positive sideways acceleration indicates a decreasing rate of movement left or an increasing rate of movement right and vice versa for negative sideways acceleration. This analysis is of counter rotated data so in real world terms, tracking at 1° was moving increasingly in the opposite direction to the target trajectory, and tracking at >1° was moving increasingly too much in the direction of target trajectory (see trajectory plots Figure 2-13 and angle time series Figure 2-15). The position errors at 1° did not change with repetition, indicating that participants deemed no change was necessary i.e. they believed their tracking was appropriate. An angular deviation of only 1º might be small enough not to be noticed, so the participants assumed that the trajectory was vertically down. Or, the small deviation might have been noticed at some level, but participants expected the angular deviation, which in natural circumstances would diminish, to quickly tend to zero, and therefore tracked accordingly. At larger angular deviations it might be obvious that the angular deviation was not reducing, so they tracked in that direction. In Chapter 4 (using the same stimuli) I report a confirmatory finding that conscious discrimination of target path angle at 1º either side of the vertical is more likely to be reported as vertically down than it is to be reported correctly. In that chapter I conclude that this effect is likely to represent an assumption that gravity draws targets downwards. Hubbard & Bharucha (1988) and Nagai et al. (2002) found similar implicit assumptions of gravity's effects when examining reports of the final position of a suddenly disappearing target moving in straight lines on a computer monitor.

Errors for angle conditions of >1º showed tracking moved towards the side that the target was moving towards. Changes in errors with repetition, indicating learning, revealed that participants typically *increased* their error by tracking increasingly too much in the direction of target motion. Following the first attempt, the increasing sideways component to tracking occurred at between 200-400 ms from a previous close to zero sideways error. It is not clear why this happened. It suggests that several hundred ms of tracking allowed acquisition of information on the movement of the target away from vertical, and so correction to sideways error, which in fact were larger than required (over-compensation).

Large negative position error (Figure 2-20) and rapid increase in negative error (from near zero) in the time series (Figure 2-15) for first attempt tracking at 90° shows an expectation that the target would descend. This indicates an internal model issuing a prediction that the target would descend. This could be on the basis of previous real-world experience, but also because most experimental trials included a substantial downwards component so there may be no expectation of a purely horizontal trajectory. Tracking at 45° also showed tracking initially descending vertically despite practice (over the time frame 0 to 400-550 ms depending on the attempt number). However, tracking at 45° differed from that at 90° because though the deviation towards the vertical decreased with practice it nevertheless persisted. This is a very strong indication that an internal model was predicting a natural evolution to observed movement, though was adapting to the observation that the movement was contrary to expectation. This concurs with the fact that judgments of the position of targets moving in straight lines is guided by the expectation that gravity will influence target movement (Hubbard & Bharucha, 1988; Nagai et al., 2002). This represents a prediction of future target position based on previous experience. In our experiment, manual tracking, being ahead of the target, is necessarily reliant on the prediction of target position. In at least the atypical directions of 45° and 90°, this prediction appears to factor gravity's effect on the target despite prior and real-time visual information to the contrary (though practice does reduce the influence of this assumption).

2.4.5.3 Manual tracking concluding remarks

The key findings are that:

- Tracking of descending targets is ahead of and faster than the target itself whereas tracking ascending targets is behind the target, slower than it and accelerates less quickly.
- Tracking of diagonally and horizontally moving targets shows an expectation of downwards movement despite practice.
- Tracking a target moving at 1° off the vertical is consistently towards the vertical.

These findings indicate that participants had an expectation that the virtual target would be affected by gravity acting vertically downwards (for which there is precedent (Hubbard & Bharucha, 1988; Le Séac'h et al., 2010; Nagai et al., 2002; Senot et al., 2012, 2005; Zago & Lacquaniti, 2005; Zago et al., 2004)). This may be the result of predictions by an internal model of gravity influencing ongoing behaviour.

2.4.6 Laser Tracking

2.4.6.1 Laser tracking in-line component

The main findings are:

- Tracking was behind the target but became less behind with practice.
- Participants appear to rely more on feedback provided by the laser spot than on any internal model of target motion.

Laser tracking was behind the target by a similar amount for all angle conditions

(Results 2.3.4.4) whereas manual tracking was ahead of the target and varied between angular conditions. Load forces and the effects on hand kinematics imposed by hand-held objects are thought to be predicted by an internal model of motor apparatus (Flanagan & Wing, 1997; see also studies on tool use: Imamizu & Kawato, 2012 & Imamizu et al., 2000) so the laser unit itself is unlikely to affect tracking output (see also Discussion 2.4.4). The fundamental difference between the manual and laser conditions is the presence of perfect feedback of tracked position during laser tracking. When laser tracking, the laser spot can be superimposed onto the target (allowing zero error) but superimposition when manual tracking would occlude the target (see Discussion 2.4.5.1). However, this only explains why manual tracking is below the target (ahead for descending target and behind for ascending targets) and not why laser tracking is *always behind*. Regardless of superimposition, the error pattern between the two conditions should be similar if the control output is the same. Because they differ I suggest that control output varies dependent on the method of tracking/interaction with the target.

Zago et al. (2004) found virtual interaction (button press) with a free-falling target elicited a 1st order prediction of its future position whereas haptic interaction (punching) of the same targets elicited 2nd order prediction. They concluded that the method of interaction influenced the perception of target mass that in turn altered the prediction of its movement. The pseudo-virtual nature of laser tracking in our experiment may cause assumption of a mass-less target, elicit first order movement and lead to underestimation of travel. However, if this were the case there would not be the observed reduction in position error from first to second and third attempts for every trajectory. Furthermore, first-order prediction alone would lead to tracking patterns being alike for all angle conditions, but horizontal and ascending tracking differed from tracking at other trajectories: position errors were significantly larger than vertically down and there was no catch-up movement at ~300 ms that existed for other tracked trajectories. Also, when tracking was horizontal or ascending, the attempt errors at the second and third attempt had reduced to nearly that of the other trajectories from a first attempt error that was much larger. These features indicate that targets moving with horizontal and upwards trajectories were not expected to accelerate in the same way as targets moving in all other directions which had vertically descending components. Some prediction of normal gravity appears to be incorporated into, at least, the first tracking movement of a target moving in any direction i.e. there was an expectation that acceleration should be downwards.

Prediction of target motion was evident when manual tracking so it seems likely that when laser tracking, participants could still have used predictive control, but the immediate visual feedback of tracked position may have prompted reliance on the on-line comparison of feedback (tracked position) to target position. In Discussion 2.4.9.1 I show that gaze tracking was behind the laser spot by the same distance that gaze tracking in other conditions was behind the target and suggest that this indicates gaze following the indicated tracking location (laser spot) rather than the target location. This too suggests reliance on feedback because participants followed the laser spot.

2.4.6.2 Laser tracking sideways component

The main findings were that:

- There was a small leftwards tracking offset.
- When tracking a target moving <45° from the vertical there was little sideways error. However when the angle was ≥45° the error was large at first but reduced to near that of shallower angle following a single trial.

There appears to have been a general leftwards tracking offset though less severe than that in the manual condition. The offset is clearest in the starting error (i.e. 1 ms) of the angle time series (Figure 2-28) and accounts for the negative sideways error for vertically down, slight positive error for vertically up (caused by 180° counter-rotation), and the larger total errors leftwards for leftwards moving tracking than total errors rightwards for rightwards moving tracking. However, it does not account for the greater rightwards movements than leftwards movement seen in velocity errors and over compensation in the direction of target movement seen in the time series. Time series data concur with the angle data in that there is little sideways movement when tracking leftwards and some small movement over compensating for the direction of target trajectory for rightwards angles. Generally there was less sideways movement relating to the target than when tracking manually and what appears to be a greater capacity to improve tracking with practice despite initially very low errors.

At angles <45° the position errors for leftwards angles tended to be left of the target and for rightwards angles they tended to be right of the target. Velocity errors and the angle time series show that tracking was generally moving sideways too much in the same direction as the target and this error increased following the first attempt. This was also found when manual tracking, but unlike manual tracking there wasn't the trend of tracking towards the vertical when the target moved at just 1° away from the vertical.

The time series plots show that second and third attempt diagonal (45º) tracking errs leftwards (real-world towards downwards) and then overcompensated rightwards (real world diagonally upwards). The initial downward movement suggests that there is an expectation of decreasing horizontal movement as would naturally occur. This may not occur for horizontal tracking because such a motion may be too unnatural to elicit such expectation. However, Hubbard & Bharucha (1988) and Nagai et al. (2002) found horizontal motions can elicit predictions of gravitational effect on target motion: but the distances travelled by the targets in those experiments were much less than the distances travelled by targets in our experiment so the 'strength' of exposure may have had an effect. The level of interaction with the target may well be important and is also different – full tracking in our experiment compared to just a single point indication at the end of stimulus presentation for Hubbard & Bharucha (1988) and Nagai et al. (2002).

Much larger first attempt error than second and third attempt error results in large position error SDs in angle data when tracking at 45º or 90º (Figure 2-37). Most trajectories descended, and with quite small angular deviations away from vertical (≤5°) so it was clearly not unreasonable for participants to track downwards during the first part of the first attempt when a new target trajectory was introduced, and indeed the trajectory plots and time series showed this to be the case (Results 2.3.4.2 & 2.3.4.3). Furthermore, sideways errors reduced to that typical of all other angle conditions following only a single stimulus presentation. This differs from manual tracking at 45º where tracking slightly more towards vertically down persisted throughout attempts.

Feedback from the laser may have allowed a fine enough comparison of tracked position to target position to reduce sideways error compared to the manual condition where such clear feedback this was not available. Alternatively, because laser tracking trailed the target, participants may have estimated the target's real-time sideways position based on previously seen travelled path and so minimised error (rather than using prediction of future path that would not work well for a target 'falling' in a straight line at 45º, resulting in larger errors).

2.4.6.3 Laser tracking concluding remarks

When laser tracking, there may have been some influence of an internal model predicting the influence of gravity on a free-falling target as evidenced by clear pattern difference in the errors for diagonal and horizontal tracking compared to angles much closer to vertical. However, following the first tracking attempt, participants appear to have been relying on the precise and powerful feedback of the laser spot in order to compare instantaneous tracked position to target position, resulting in tracking slower than, and behind, the target. This homogenised in-line tracking such that the errors when tracking at shallow angular deviations vertical (≤10°) were similar. This evidence does not argue in favour of laser tracking being facilitated by an internal model of gravity.

2.4.7 Gaze Only Tracking

2.4.7.1 Gaze only tracking in-line component

The main findings are that:

- Gaze tracking was behind the target overall.
- The mean error was similar at every tracked trajectory apart from when tracking 90° rightwards.
- After one trajectory presentation participants were able to predict the upcoming position of the target.

Tracking at every angle (except 3° right) was behind the target (positive error) (Figure 2-43) and the distance behind was similar for each angle except 90° right for which tracking was significantly further behind than when tracking vertically down. Tracking at 45° and vertically upwards was slightly further behind than when tracking the near-vertical angles. Tracking was always slower (positive velocity error) than the target and the pattern of error was the same as for position measures. The general pattern of gaze errors was even more consistent across angles than the laser pointing errors seen in the laser condition. This could arise if participants' interpretation of successful gaze tracking was broad, a 'good enough' approach. But the time series plots (Results 2.3.5.3) show that following the two catch-up saccades (at ~250-300 ms and ~525-650 ms) that occurred in the second and third tracking attempts at all angles (apart from 90° rightwards), the position error was reduced to near zero, indicating that participants' gaze tracking was in fact highly localised not generalised.

Attempt errors show that a single presentation of target trajectory was sufficient to significantly reduce position errors and when tracking trajectories more than 1° from vertical (see time series plots (Figure 2-41) that also show that the position error became less variable with practice).

Tracking a target accelerating horizontally (90° rightwards) generated larger tracking errors than when tracking a target with *some* vertical component to its movement (such as 45° rightwards) even when such a trajectory might be completely unnatural (i.e. accelerating vertically upwards). It therefore appears that of all the directions tested, a horizontally accelerating target was the most difficult to track. This presumably reflects an expectation, represented in an internal model, that there should be at least *some* vertical component to motion when under the effect of gravity. This is a reasonable expectation since in the real world an object launched in any initial direction, even horizontally, would accelerate downwards, whereas acceleration sideways is completely unnatural. The greater errors seen for horizontally accelerating targets are therefore evidence for an internal model predicting vertically downwards acceleration.

Following a single presentation of the target's trajectory for all angle conditions apart from horizontally, participants were able to predict the future position of the target and orientate to that position when gaze tracking.

2.4.7.2 Gaze only tracking sideways component

The main finding is that:

- When tracking a target descending at 45° away from the vertical, or horizontally, or ascending, the sideways error was greater than when tracking near vertically downwards.
- When the target moved horizontally, there was a downwards component to tracking. This probably reflects an expectation that even a horizontally moving target should acquire a downwards component due to gravity.
- Gaze tracking was consistently offset to the left of the target by ~50 mm. This appears to be a small technical (offset) error that does not affect derivatives and was not present in the calibration plots (see Appendix 7.3.3.3).

Starting errors were approximately 50 mm left of the target for all descending tracking, and approximately 100 mm for ascending tracking (see time series and trajectories plots [Figure 2-42 & Figure 2-40]). Though pointing offsets were found when manual and laser tracking, they were typically <10 mm. As there is no obvious reason why participants should gaze to the left of the centre of the target but ~25 mm inside its perimeter (target radius was 75 mm) it is possible that there is a ~50 mm error in the gaze vector and calculated intercept. The size of the error is fortunately smaller than the target, and the derivatives of tracked position are of course not affected by any constant offset. Indeed the velocity and acceleration errors suggested very little and equal sideways movement relative to the target. Also the error in calculated gaze location during calibration was found to be very small (see Appendix 7.3.3.3). The apparent offset is most likely, therefore, to represent simply a limitation of the accuracy in the method for calculating 3D gaze vectors for a freely moving head.

As a result of the initial offset and small overall change in direction of tracking movement left or right (velocity error - Figure 2-48), tracking was, overall, left of the target in all angle conditions apart from vertically upwards which was right of the target for the same reasons (Figure 2-47). However tracking horizontally moving targets (90º rightwards) the sideways error is leftwards (real world downwards) for different reasons. The time series plot (Figure 2-42) for this angle condition shows that the tracked position on the screen began to descend (i.e. increase in negative error) following 100 ms at the first attempt and 200 ms at the second and third attempts. These features could arise from an expectation of a free-falling target's height decreasing. Another possibility is that the error may arise from miscalculation of gaze vectors; but there is nothing to suggest such an error in any other angle condition. In particular when tracking at 45º right (the condition with the next most change in horizontal position) I would also expect, if the result at 90º right reflects technical limitations, that tracked vertical position would decrease but in fact it *increases* steadily at 350-400 ms (Figure 2-42). This feature of increasing the horizontal movement of tracking in the direction of target motion is also present when tracking at nearer vertical angles. Consequently, the evidence is that the downwards tracking of a horizontally accelerating target is indicative of output from an internal model predicting a gravity field.

There was little clear pattern to the interaction of tracking angle and repetition, though the total position error did typically decrease (but not insignificantly) with practice. As indicated by the small SDs in the total errors (Results 2.3.5.7) this was a very small change in error with repetition.

2.4.7.3 Gaze only tracking concluding remarks

Accurate smooth pursuit of the target was not possible: tracking was typically behind the target throughout the period analysed but two saccades that were similarly timed in all angle conditions (apart from 90º rightwards) at the second and third attempt brought gaze successfully onto the target. That gaze caught the target after falling behind and because there was a persistent downwards component to tracking horizontally suggests that there was prediction of movement for a freely moving target using an internal model.

2.4.8 Gaze Tracking in the Manual Condition

2.4.8.1 Gaze tracking in the manual condition in-line component

The main finding was that there was little difference between gaze in the manual condition and gaze in the gaze only condition suggesting that:

- Gaze tracking with concomitant manual tracking has little effect on gaze tracking output.
- Gaze tracking in the manual condition was focussed on the target rather than the fingertip.

One might expect that gaze tracking in the manual condition (GM condition) would be similar to the manual tracking itself i.e. tracking *ahead of* the target but in fact it bore a greater resemblance to gaze tracking in the gaze only (GO) condition i.e. tracking *behind* and with corrective catch-up saccades. The differences between the two gaze conditions are seen in plots showing different angles separately to visualise any interaction effects with repetition. Errors at any particular angle are typically greater in GM than GO but there is greater decrease in those errors with practice; compare errors at 1-5° right in Figure 2-55 (GM) to Figure 2-43 (GO). As in the gaze-only condition, gaze tracking during manual tracking, at least in the second and third attempts, exhibited error that typically reduced to near error through catch-up saccades (except for 90° right).

The addition of manual tracking does not appear to affect gaze tracking. The similarity in errors suggests that gaze in both these conditions was controlled in the same way. It appears that gaze was similarly focussed on the target in both conditions. By focussing on the more distant target, there would of course be a double image of the nearer tracking hand during manual tracking with both eyes open. This means that two potential vectors were available to control manual tracking, one originating from each eye. Our analysis (Results 2.3.1 & Discussion 2.4.1) identified that the vector from the dominant eye yielded lowest calculated manual tracking errors, confirming that the visually dominant eye was also dominant for manual control purposes. The similarities between gaze tracking in the manual condition and gaze tracking in the gaze only condition lead us to the same conclusion of tracking control: that participants seemingly used an internal model of gravity to predict the upcoming position of the target and orient gaze to that location.

2.4.8.2 Gaze tracking in the manual condition sideways component

The main findings are that:

- Tracking was offset to the left.
- There was a rightwards movement to tracking.

The angle trajectory plots (Figure 2-54) reveal a clear difference in the sideways components of gaze position between gaze tracking in the manual condition (GM condition) and gaze tracking in the gaze only condition (GO condition). In all other conditions thus far described the sideways component of tracking has been too much in the direction of target motion and such error has increased as the angular deviation from the vertical has increased, but when gaze tracking in the manual condition this was not found to be the case. Rather, all leftwards tracking trajectories greater than 1° moved with a close to zero change in sideways position from start to finish whilst all remaining tracking trajectories (apart from 90° right and vertically upwards) were moving rightwards and the amount rightwards increased as angular deviation from the vertical increased (similar to gaze in the gaze only condition (Figure 2-42)). Trajectory plotting (Figure 2-52) of an ascending target showed that tracking moved rightwards (leftwards before counter-rotation). Velocity errors (Figure 2-60) confirms the finding suggested by the trajectories that there was no sideways movement when tracking for angle conditions of 5° left to 2° left, and that there was movement rightwards when tracking in angle conditions of 1° left to 45° right.

This all suggests that gaze tracking in this condition was offset by an anti-clockwise rotation. But such a rotational offset was not found in any other condition so the target position and centre of rotation used for counter-rotation must be correct and so must the calibration used in gaze tracking. Slippage by yaw rotation of the ASL-501 headband around the head could conceivably cause anti-clockwise rotation but because there is no evidence of such rotation in the GO condition I conclude that this rotational offset is in fact a real tracking pattern rather than a technical artefact. No pattern of asymmetric movement was found in the manual tracking so this may be an effect of interference because of the dual task though I do not know why this effect is asymmetric. Participants may have translated and rotated their head to gaze directly down the length of their pointing finger though no such behaviour was observed by the experimenter (i.e. participants behaviour in GM matched that in GO). The angle conditions where there was no sideways movement identified in the trajectory plots (2°-5° leftwards) showed no change in velocity interaction error (Figure 2-63). This supports the idea that this finding is behavioural and not a result of calculation error.

The remaining significant features (tracking patterns at 45° and 90°) are very similar to those identified in GO. As such, I believe that gaze tracking during manual tracking was controlled in the same way: most likely by an internal model,

2.4.8.3 Gaze tracking in the manual condition concluding remarks

Gaze tracking was only slightly affected by the addition of manual tracking in that gaze tracking was marginally further behind in manual condition than it was in the gaze only condition. Further there was greater improvement on observed error with practice. Because the patterns identified indicate that gaze tracking was relatively unaffected by a second task, i.e. that there was no overall difference between GM and GO (Discussion 2.3.2), I believe gaze tracking control during manual tracking was independent of manual tracking control and that such control was likely to be influenced by an internal model predicting effects of a gravity on a freely moving object.

2.4.9 Gaze Tracking in the Laser Condition

2.4.9.1 Gaze tracking in the laser condition in-line component

The main finding is that gaze follows the laser spot rather than the target.

Though mean errors were much larger, the pattern of mean errors between angles for gaze in the laser condition (Gaze-Laser) was the same as in the gaze only condition (Gaze-Only) and gaze in the manual condition (Gaze-Manual): similar errors when tracking at angles <45°, larger errors when tracking at 45° and the largest when tracking at 90° (Results 2.3.7.4) i.e. gaze tracking was slower and further behind the target in Gaze-Laser than it was in Gaze-Only or Gaze-Manual. Position errors within each angle reduced with repetition for all angles apart from 90° rightwards, and more clearly than in the other gaze conditions. This reduction is also clear in the attempt position errors (all angles pooled) and the angle time series plots (all attempts pooled). The angle time series errors (Figure 2-66) are similar for each attempt and at each angle though that for 90° rightwards is steeper and leads to the larger errors seen in the pooled angle measures. Unlike Gaze-Only and Gaze-Manual, the first saccade at 250-300 ms typically did not reduce tracking error but rather temporarily slows are pauses increasing error. The pattern of errors seen here for gaze during laser pointing was similar to the pattern of errors for laser tracking itself; and these were both different from the error patterns of other tracking conditions (manual tracking, Gaze-Only and Gaze-Manual).

We must assume that participants' gaze tracking was to the best of their ability in the Gaze-Only and Gaze-Manual conditions. The principal difference in the laser tracking condition is that participants had instantaneous and accurate feedback of tracked position. As laser tracking was behind the target (Discussion 2.4.6.1) and gaze tracking in the laser condition was further behind gaze in the other gaze conditions, I considered whether participants were following the *laser spot* rather than the target with their eyes. Gaze-Only and Gaze-Manual tracking was behind the target, as indeed was laser tracking itself (of the target). But gaze during laser tracking was even further behind than the tracking laser spot. In fact, gaze during laser tracking was behind the laser spot by the same amount as Gaze-Only or Gaze-Manual was behind the target (apart from when tracking at 90° rightwards and vertically upwards): Figure 2-76. This indicates that gaze during laser tracking, rather than following the target, actually followed the laser spot in the same way that gaze tracking was pursuing the target in the other gaze conditions.

Though gaze tracking control in the manual condition was not affected by concomitant manual tracking, this does not mean that the two were operated independently, it seems likely that they were operating under the same instruction. This also appears to have been the case for gaze tracking control and laser tracking control in the laser condition - the laser spot prompted reliance on laser feedback in the laser condition (Discussion 2.4.6) and appears to have done so for gaze with concomitant laser tracking.

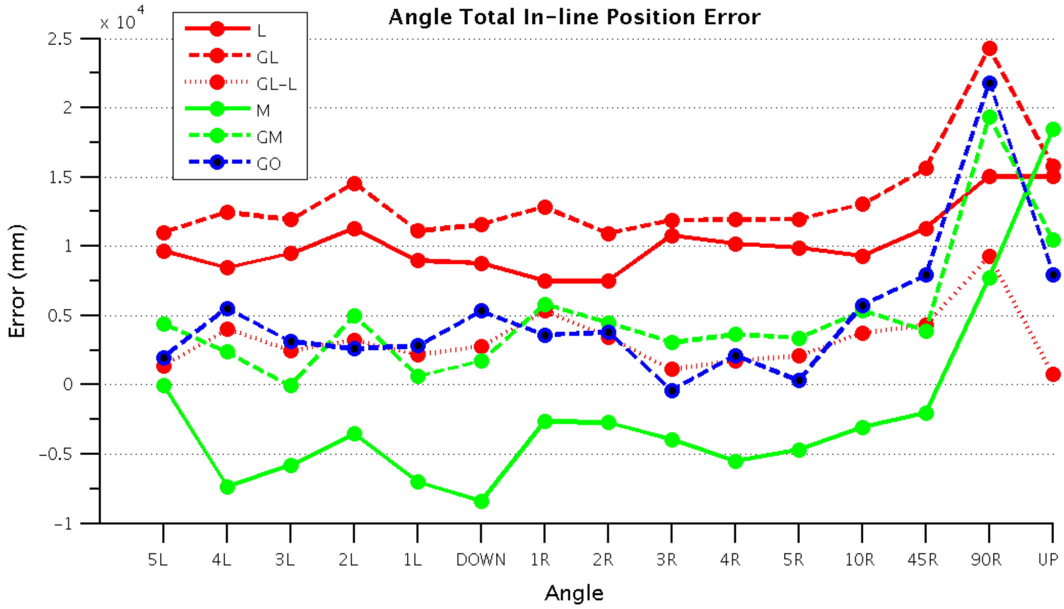


Figure 2-76. Total in-line errors when tracking in different directions. Traces show manual tracking error (M), laser tracking error (L) and gaze tracking error under different conditions (GO = gaze only, GM = manual condition, GL = laser condition). In addition, the dotted red line shows gaze relative to pointing intercept in the laser condition (GL-L).

2.4.9.2 Gaze tracking in the laser condition sideways component

It is clear from the preceding section dealing with the in-line component of tracking that Gaze-Laser was following the laser spot rather than the target. This must also be true for the sideways component of tracking because the data set is identical for both components.

2.4.9.3 Gaze tracking in the laser condition concluding remarks

When not tracking with the laser, only the target was visible on-screen and participants' gaze tracked that (the target) with certain in-line and sideways errors. When tracking with the laser, so that there was both a target and a tracking laser spot visible on-screen, gaze tracked the laser spot (not the target) and with similar in-line and sideways errors from that spot.

2.4.10 Believable stimuli

What participants believe about an object is important for how they relate to it. When virtual targets are not considered 'real', participants will interact with them as though they have no mass i.e. no acceleration due to gravity (Zago, Bosco et al. 2004). However, an immersive virtual environment has elicited the assumption of mass for virtual targets which caused participants to interact with targets as though they would behave naturally i.e. downwards acceleration due to gravity (Le Séac'h et al., 2010; Senot et al., 2005). In this experiment, the evidence for prediction of target motion in all conditions other than gaze during laser tracking (where gaze followed the laser spot, and the spot was tracking target motion predictively) indicates that participants sufficiently believed the target represented a real world object that had mass and would behave in a 'natural' way. Furthermore, several participants verbally reported the realistic nature of stimuli. One participant reported constantly expecting the target was going to bounce off the floor when it reached near ground level. This suggests prediction of future target movement in a completely physical way even after it had disappeared. Such extrapolation has been found previously when participants were asked to report the final position of a target that suddenly disappeared following movement (Finke et al., 1986; Finke & Freyd, 1985; Hubbard & Bharucha, 1988; Hubbard, 1990; Nagai et al., 2002).

2.4.11 Duration of target visibility

The size of the screen's rendering area (Figure 2-1) limited the target's travel time (see Methods 2.2.3&2.2.5). Tracking was assessed over 730 ms, sufficient time to overcome visuomotor delays of 150-200 ms (Zago et al., 2008) though it is still a short period in which to identify acceleration at *g* and to learn from ones errors.

The time series plots for all tracking conditions show changes in the pattern of attempt errors with repetition (i.e. from first to third attempt) – typically, decreases in the distance behind targets or increases in the distance ahead. This modification of tracking behaviour confirms that duration of target visibility was sufficient to collect information on tracked position relative to target position. Furthermore, within an individual trial, catch-up saccades when gaze tracking in isolation and in the manual condition, indicate sufficient time to judge target motion. Thus the presentation time was satisfactory to both observe tracking behaviour and infer underlying control mechanisms.

2.4.12 Control by internal modelling not by 'direct perception'

In Chapter 1 and the introduction to this chapter I discussed 'direct perception' as an alternative to internal modelling. Briefly: 'direct perception' theorises that only information available in the immediate visual scene, and not derived from experience as with internal modelling, is used to anticipate future target position or interception points.

This experiment can differentiate between these two theories because the target's only variable property is travel direction. The visual scene contains all of the information required to predict target motion for every trial so if 'direct perception' were employed then one would expect near identical tracking for every trajectory. However, if an internal model of gravity exists and is predicting that targets accelerate downwards at *g* then I would expect differences in the tracking of each trajectory. The evidence I obtained for every tracking condition (manual and laser tracking, gaze tracking in these conditions and gaze tracking in isolation) is that tracking errors varied systematically depending on target direction. Specifically I have found evidence that:

- Tracking ascending targets is slower than that for descending targets.
- Tracking of targets moving with the smallest deviation from vertical tested (1°) is qualitatively different from tracking of targets moving with greater deviations. At 1°, tracking is more towards the vertical than the direction of target movement. At larger deviations (2-10°) tracking is further away from vertical than the target.
- Tracking errors typically increase as the angular deviation away from the vertical increases up to 10°.
- Tracking is bowed downwards towards the vertical when targets descend 45° from the vertical (and persistently when manual tracking i.e. without improvement with repetition).
- Tracking of a horizontally moving target also shows lower acceleration, and greater errors, than when tracking targets moving downwards.

These differences cannot be explained in 'direct perception' terms and so argue more in favour of visuomotor control achieved through an internal model of acceleration due to gravity (*g*). These data are, however, not without outliers. For example in Figure 2-16 we see a trend for mean total in-line position errors to increase from 2° to 4° leftwards in the direction opposite to that which would be expected if an internal model of gravity operated. Here it is important to note that noise is inherent in this type of data – participants' self-judged tracking accuracy is analysed by extrapolating their arm movement onto a distant plane intercept – so general trends presenting throughout the data set should be considered over individual discrepancies in data plots.

Gaze behaviour also shows differences depending on target direction that suggest internal modelling. There is some reason for caution in interpreting the findings on horizontal (rightwards) gaze tracking for extreme eye-in-orbit yaw movement (gaze angles close to the limit of the calibration angles) where I observed a persistent decrease in the vertical tracked position at the far right, or the end of the trajectory, for rightwards moving targets (Figure 2-42, Figure 2-54 & Figure 2-67). However, the vertically ascending and descending targets require no eye-in-orbit yaw change at all, and so differences between the tracking errors for those two trajectories are not affected by that technical consideration and again reveal an expectation for control purposes that objects accelerate downwards at under gravity.

Most tracking of targets with an angular deviation of <10° was very similar indicating that the lower error for vertically descending tracking (compared to upwards) was not by chance. Therefore, it appears that an internal model of gravity and not 'direct perception' was used by participants in all tracking method conditions.

2.4.13 Is the suggested internal model of gravity directionally tuned?

Studies of interception of targets descending and ascending at *g* (9.81m/s^2) have shown that ascending targets are predicted to decelerate and descending targets are predicted to accelerate despite participants' observations to the contrary (Senot et al., 2012, 2005). This has been taken as evidence that an internal model of gravity predicts the future position of moving targets using the observed direction of motion. These studies only examined the simplest directions of motion (up vs. down) but estimation of the final position of a target that suddenly disappears during a straight line horizontal motion is forward and below the true final location (Hubbard & Bharucha, 1988; Nagai et al., 2002) suggesting that prediction of gravity's effect is applied to observed directions of motion other than on the vertical. A main aim of this study was to investigate the directional tuning of an internal model of gravity beyond that of simple vertical or horizontal motion.

In all tracking methods tested, it was the case that tracking of ascending targets was behind tracking of descending targets. The differences found in tracking between the ascending and descending target conditions are precisely what one would expect if an internal model of gravity were predicting the future position of the observed target, because ascending targets should decelerate and descending targets should accelerate. Thus it is logical that one's tracking for ascending targets would be slower than for descending targets. These direction-dependent predictions of target motion existed despite the presence of information (the stimuli) contrary to the prediction. Similar prediction of gravity's effect regardless of observed motion has been found previously by several groups using a variety of procedures though only ascending and descending targets have been examined: real 'descending' targets in a 0*g* environment (McIntyre et al., 2001); virtual interaction with virtual *approaching* descending/ascending targets at -1*g*, 0*g* or 1*g* (Le Séac'h et al., 2010; Senot et al., 2012, 2005); and physical interaction with virtual descending targets at 0*g* or 1*g* (Zago et al., 2004, 2005). This indicates that internal model predictions are robust.

When participants were manually tracking I found evidence of prediction of a vertical descent (indicated by tracking) when targets moved at 1º left or right of vertical – sideways tracking error was in the direction of the vertical in those angular conditions (see Discussion 2.4.5.2). Tracking towards the vertical was not found when the target was moving at >1º from the vertical which suggests either some threshold in the detection of angular deviation, or an aspect of prediction unique to trajectories very close to a vertical descent. Though there may be a detection threshold (i.e. at >1º deviation from the vertical it was obvious that the target was moving sideways), such a detection limitation does not explain why tracking was for some time, and without 'wandering', accurately on the vertical and not elsewhere. Over the range, 0±1º from the vertical, tracking was well maintained on the vertical, suggesting that the vertical (as a direction) is 'known' to participants or internally modelled. In natural circumstances where no sideways force is applied to a free-falling target, the target will fall vertically and any initial sideways deviation (due to any initial horizontal component of velocity) will diminish over time. If this principle – vertical of trending towards the vertical movement – were a component in the prediction of free-falling targets it would explain the error pattern at 0±1º angular deviation from the vertical. Another important indicator of internal model directional tuning is from the 'bowed' manual tracking at 45º (Figure 2-13). The first attempt at tracking this angle was behind the target but deviated downwards initially and though the arc of the bow became shallower with practice, there was still a deviation towards vertically down when the tracking was ahead of the target and, crucially, when the target's trajectory was known (i.e. in second and third tracking attempts).

These are indicators that there is a model predicting decreasing deviation of target trajectory from vertical as would be expected naturally in the real-world.

2.4.14 The importance of multiple tracking methods

The use of several different tracking methods is a great strength of this study, as it revealed that tracking output is affected by tracking method. Despite the differences between the output for each method condition, the interpretation of results from each has led us to the conclusion that there is an internal model of gravity that is tuned towards vertically down. Had I only tested a single tracking method I might have reached a different, erroneous or at least less 'global', conclusion. Two such examples are:

- If interpreting only laser tracking then I might have suggested that tracking is based mainly or only on feedback of tracking position given by the laser spot (Discussion 2.4.6), with the spot following the target and the eyes following the spot; whereas when manual tracking (without such accurate visual feedback) control appears to be by application of an internal model of gravity (Discussion 2.4.5). Furthermore, without the condition of manual tracking by finger pointing, I might have overlooked the model's directional tuning which was clearer when manual tracking than when laser tracking (which showed more consistency across directions) (Discussion 2.4.13).
- If interpreting both gaze tracking in isolation, and gaze tracking in the manual condition, then I might have suggested that the addition of a second task has no effect on gaze tracking; whereas in fact the substitution of manual tracking with laser tracking had a very significant effect on gaze tracking output (see Discussion 2.4.3).

2.4.15 Conclusions

- The CNS probably constructs and maintains an internal model of gravity that appears to be directionally tuned towards vertically down.
- This model predicts that the movement of observed 'freely-moving' stimuli will be in a natural real-world manner i.e. vertically downwards or in a direction tending increasingly to vertically downwards over time.
- Practice at persistently unnatural trajectories can modify the model but 3 presentations were insufficient to completely reorient the model to the presented direction of motion (there remained differences in errors at the third attempt compared to errors seen when tracking a target moving vertically downwards).
- The natural method of pointing is by the dominant eye gazing past the tip of the index finger and towards the target.

- Finger pointing has little or no effect on gaze tracking whereas when one provides augmented tracking feedback (a laser spot), gaze will follow such feedback rather than the target to be tracked.

2.4.16 Further work

A. Uncertainty of direction. Participants were not aware of the direction that the target would move at the first attempt of each angular deviation, apart from during the ascending trajectory where the start position of the target implied an ascending trajectory. Because of this uncertainty, the changes in tracking error from the first to the second attempt might partly reflect reluctance to commit to a ‘track’ when the trajectory is unknown i.e. participants may track slowly (behind the target) initially in order to gain an idea of the trajectory and then at subsequent attempts, when the trajectory is known from recent history, they may ‘commit’ more fully to tracking. Consequently any change in tracking output with repetition might be partly due to a psychological effect arising participants’ uncertainty, rather than changes in the parameters of the tracking controller/motion predictor. A simple test to distinguish between these two possibilities would be to indicate the direction in which the target was about to move using an arrow before presenting the stimulus to track. If the same pattern of data arose as was found in the current experiment then I would conclude that changes in tracking output are due to the changes in the tracking controller/motion predictor (rather than a psychological effect due to uncertainty). Whereas, if the first attempts in a new direction in the proposed experiment changed to become similar to the second attempts in the current experiment then I would conclude that uncertainty of direction of movement in the present study was indeed an important factor.

B. Perception of horizontal. In a virtual interception task where scene orientation and gravity (which dictated the acceleration/deceleration for descending/ascending targets moving in straight line) can be inverted independently, performance is best when the scene and gravity orientation are congruent regardless of the orientation of the scene (Zago, La Scaleia, Miller, & Lacquaniti, 2011) i.e. performance was best when gravity acted in the direction of the ‘ground’ in the virtual scene even if the scene was inverted (ground was up). The authors concluded that participants oriented gravity from clues in the visual scene rather than using viewer-centric (participants orientation) or gravicentric (real-world down) frames of reference. In our experiment, no clues of vertical were given in the projected image and though the laboratory was darkened there was sufficient light to make out straight line aspects of the room and apparatus (such as light units, pillars and the projection screen frame) that imply a vertical and consequently imply a direction for gravity. An interesting progression for this experiment would be to completely mask any real-world clues to vertical and imply a horizontal that is congruent with target trajectory angle i.e. imply a ‘ground’ that is perpendicular to the target trajectory. If participants do indeed orient gravity by clues in the visual scene then I would expect tracking errors to be similar for all trajectory angle conditions, or at least for the greater errors I saw for directions away from vertical to be reduced. The effect found by Zago et al. (2011) was powerful. Despite the fact that the physical tracking action involved in our experiment (movement of the whole arm) might make it impossible to achieve a complete reorientation (up to even an inversion) of a gravity frame of reference, I might at least expect that our finding of tracking towards the vertical for angular deviations of only 1° would disappear.

C. Shallow angular deviations from vertical. When manual tracking there was an interesting and unresolved feature: at 1° angular deviation was towards the vertical but tracking at 2° deviation showed too much sideways movement. In Discussion 2.4.5.2 I suggested that participants may either have not noticed the 1° deviation and assumed a vertical descent, or did notice it but assumed a natural tendency towards vertical during freefall. Also, I suggested that the ‘overcompensation’ for sideways movement at >2° deviation might be because tracking was ahead of the target, but such ‘overcompensation’ was also found when tracking trailed the target. It would be interesting to test further the angular range of 0-2° in <1° increments to more accurately define the threshold for ‘down-ness’.

D. Transient target disappearance. One participant reported expecting descending targets to bounce off the floor after they disappeared from the screen. This strongly indicates prediction of future target position (and indeed, of other aspects beyond acceleration due to gravity – conservation of momentum during collisions. It is not known from this experiment or other studies how accurate or how common such predictions might be). Single-unit recordings in the (cat) cerebellum (which is a candidate location for internal models (Cerminara et al., 2009; Ebner & Pasalar, 2008; Imamizu & Kawato, 2009, 2012; Imamizu et al., 2000; Wolpert et al., 1998)) have shown that an internal model can predict the future position of visual targets even during their transient disappearance. It therefore seems likely that such prediction is possible in man and so I propose a similar study to that conducted here but with longer ‘fall’ distances to accommodate three stages of stimulus: 1) A period of motion to observe target kinetics. 2) Transient target disappearance. 3) Target reappearance.

Tracking that is accurately maintained during transient disappearance or tracking that reaches the reappearance location simultaneously with the target would indicate persistent output of an internal model of gravity. The study could be simplified by only testing a vertically descending target.

2.5 References

Bays, P. M., Wolpert, D. M., & Flanagan, J. R. (2005). Perception of the consequences of self-action is temporally tuned and event driven. *Current Biology*, *15*(12), 1125–8.

Blakemore, S. J., Frith, C. D., & Wolpert, D. M. (1999). Spatio-temporal prediction modulates the perception of self-produced stimuli. *Journal of Cognitive Neuroscience*, *11*(5), 551–9.

Blakemore, S. J., Wolpert, D. M., & Frith, C. D. (1998). Central cancellation of self-produced tickle sensation. *Nature Neuroscience*, *1*(7), 635–40.

Cerminara, N. L., Apps, R., & Marple-Horvat, D. E. (2009). An internal model of a moving visual target in the lateral cerebellum. *Journal of Physiology*, *587*(Pt 2), 429–42.

Davidson, P. R., & Wolpert, D. M. (2003). Motor learning and prediction in a variable environment. *Current Opinion in Neurobiology*, *13*(2), 232–237.

Davidson, P. R., & Wolpert, D. M. (2005). Widespread access to predictive models in the motor system: a short review. *Journal of Neural Engineering*, *2*(3), 313–9.

Diedrichsen, J., Hashambhoy, Y., Rane, T., & Shadmehr, R. (2005). Neural correlates of reach errors. *Journal of Neuroscience*, *25*(43), 9919–31.

Ebner, T. J., & Pasalar, S. (2008). Cerebellum predicts the future motor state. *Cerebellum*, *7*(4), 583–8. doi:10.1007/s12311-008-0059-3

Field, A. (2009). *Discovering Statistics Using SPSS* (Third.). London: SAGE Publications.

Finke, R. A., & Freyd, J. J. (1985). Transformations of visual memory induced by implied motions of pattern elements. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *11*(4), 780–794.

Finke, R. A., Freyd, J. J., & Shyi, G. C. (1986). Implied velocity and acceleration induce transformations of visual memory. *Journal of Experimental Psychology: General*, *115*(2), 175–88.

Flanagan, J. R., & Wing, a M. (1997). The role of internal models in motion planning and control: evidence from grip force adjustments during movements of hand-held loads. *Journal of Neuroscience*, *17*(4), 1519–28.

Gentili, R., Cahouet, V., & Papaxanthis, C. (2007). Motor planning of arm movements is direction-dependent in the gravity field. *Neuroscience*, *145*(1), 20–32.

Hayhoe, M., Mennie, N., Sullivan, B., & Gorgos, K. (2004). The Role of Internal Models and Prediction in Catching Balls. *Artificial Intelligence*, *4*(8).

Hubbard, T. L. (1990). Cognitive representation of linear motion: possible direction and gravity effects in judged displacement. *Memory & Cognition*, *18*(3), 299–309.

Hubbard, T. L., & Bharucha, J. J. (1988). Judged displacement in apparent vertical and horizontal motion. *Perception & Psychophysics*, *44*(3), 211–21.

Imamizu, H., & Kawato, M. (2009). Brain mechanisms for predictive control by switching internal models: implications for higher-order cognitive functions. *Psychological research*, *73*(4), 527–44.

Imamizu, H., & Kawato, M. (2012). Cerebellar internal models: implications for the dexterous use of tools. *Cerebellum*, *11*(2), 325–35.

Imamizu, H., Miyauchi, S., Tamada, T., Sasaki, Y., Takino, R., Pütz, B., Yoshioka, T., et al. (2000). Human cerebellar activity reflecting an acquired internal model of a new tool. *Nature*, *403*(6766), 192–5.

Lacquaniti, F., & Maioli, C. (1989a). Adaptation to suppression of visual information during catching. *Journal of Neuroscience*, *9*(1), 149–59.

Lacquaniti, F., & Maioli, C. (1989b). The Role of Preparation in Tuning Anticipatory Responses During Catching -. *Journal of Neuroscience*, *9*(January), 134–148.

Le Séac'h, A. B., Senot, P., & McIntyre, J. (2010). Egocentric and allocentric reference frames for catching a falling object. *Experimental Brain Research*, *201*(4), 653–62.

Leavens, D. A., & Hopkins, W. D. (1999). The Whole-Hand Point: The Structure and Function of Pointing From a Comparative Perspective. *Journal of Comparative Psychology*, *113*(4), 417–425.

McIntyre, J., Zago, M., Berthoz, A., & Lacquaniti, F. (2001). Does the brain model Newton's laws? *Nature Neuroscience*, *4*(7), 693–4.

Nagai, M., Kazai, K., & Yagi, A. (2002). Larger forward memory displacement in the direction of gravity. *Visual Cognition*, *9*(1/2), 28–40.

Neggers, S. F. W., & Bekkering, H. (2001). Gaze Anchoring to a Pointing Target Is Present During the Entire Pointing Movement and Is Driven by a Non-Visual Signal. *Journal of Neurophysiology*, *86*, 961–970.

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, *9*(1), 97–113.

Papaxanthis, C., Pozzo, T., & McIntyre, J. (2005). Kinematic and dynamic processes for the control of pointing movements in humans revealed by short-term exposure to microgravity. *Neuroscience*, *135*(2), 371–83.

Saunders, J. a, & Knill, D. C. (2005). Humans use continuous visual feedback from the hand to control both the direction and distance of pointing movements. *Experimental Brain Research*, *162*(4), 458–73.

Savitzky, A., & Golay, J. E. (1964). Smoothing and Differentiation of Data by Simplified Least Squares Proceedures. *Analytical Chemisty*, *36*(8), 1627–1639.

Senot, P., Zago, M., Lacquaniti, F., & McIntyre, J. (2005). Anticipating the effects of gravity when intercepting moving objects: differentiating up and down based on nonvisual cues. *Journal of Neurophysiology*, *94*(6), 4471–80.

Senot, P., Zago, M., Le Séac'h, A., Zaoui, M., Berthoz, A., Lacquaniti, F., & McIntyre, J. (2012). When up is down in 0g: how gravity sensing affects the timing of interceptive actions. *Journal of Neuroscience*, *32*(6), 1969–73.

Topka, H., & Dichgans, J. (1997). The cerebellum and the physics of movement. *The Behavioral and brain sciences*, *20*(2), 266.

Virji-Babul, N., Cooke, J. D., & Brown, S. H. (1994). Effects of gravitational forces on single joint arm movements in humans. *Experimental Brain Research*, *99*(2), 338–46.

Wolpert, D. M., Miall, R. C., & Kawato, M. (1998). Internal models in the cerebellum. *Trends in Cognitive Sciences*, *2*(9), 338–47.

Wong, N., & Gutwin, C. (2010). Where Are You Pointing ? The Accuracy of Deictic Pointing in CVEs. *CHI 2010: Avatars and Virtual Environments* (pp. 1029–1038).

Zago, M., Bosco, G., Maffei, V., Iosa, M., Ivanenko, Y. P., & Lacquaniti, F. (2004). Internal models of target motion: expected dynamics overrides measured kinematics in timing manual interceptions. *Journal of Neurophysiology*, *91*(4), 1620–34.

Zago, M., Bosco, G., Maffei, V., Iosa, M., Ivanenko, Y. P., & Lacquaniti, F. (2005). Fast Adaptation of the Internal Model of Gravity for Manual Interceptions:

Evidence for Event-Dependent Learning. *Journal of Neurophysiology* (pp. 1055–68).

Zago, M., La Scaleia, B., Miller, W. L., & Lacquaniti, F. (2011). Coherence of structural visual cues and pictorial gravity paves the way for interceptive actions. *Journal of vision*, *11*(10), 1–10.

Zago, M., & Lacquaniti, F. (2005). Internal model of gravity for hand interception: parametric adaptation to zero-gravity visual targets on Earth. *Journal of neurophysiology*, *94*(2), 1346–57.

Zago, M., McIntyre, J., Senot, P., & Lacquaniti, F. (2008). Internal models and prediction of visual gravitational motion. *Vision Research*, *48*(14), 1532–8.

CHAPTER 3
THE AMPLITUDE ASPECTS OF AN INTERNAL MODEL OF GRAVITY

Internal models of gravity have been investigated in broad terms only using targets accelerating downwards or upwards, and targets accelerating (typically downwards) at *g* or moving at constant velocity. The results from the experiment described in Chapter 2 suggested that an internal model of gravity contributes to some aspects of visuomotor control related to natural motion prediction and appears to be tuned towards vertically downwards. This study investigates the amplitude aspects of that model and is the first to systematically investigate amplitude tolerances of an internal model of gravity. Participants used finger pointing, laser pointing, gaze tracking, and gaze tracking with either finger or laser pointing to track a 15 cm diameter target moving vertically downwards in a straight line with different constant accelerations (50%, 75% 90%, 95-105% and 110% of *g*). All targets travelled ~2.475 m but only the first 690 ms of movement was analysed (the longest viewable time for the fastest acceleration tested). In the absence of on-screen accurate feedback of indicated position (i.e. non-laser trials), tracking was found tuned for accelerations at *g* or slightly less than *g* indicating that participants probably used an internal model of gravity to predict the future position of free-falling targets. This tuning is evidence that participant did not employ 'direct perception' for tracking.

3.1 Introduction

We do not live in a vacuum, so the vast majority of, if not all, free-falling objects that one sees will be subject to drag (dictated by object mass, drag coefficient and relative surface area) that reduces acceleration and eventually imposes a terminal velocity. Thus, nearly all free-falling targets we see will accelerate at less than g (<9.81 m/s^2). However, many studies have compared interception performance for targets accelerating at 1g (9.81 m/s^2) and 0g (constant velocity) and concluded that an internal of model of gravity exists (Lacquaniti & Maioli, 1989a, 1989b; McIntyre et al., 2001; Senot et al., 2012, 2005; Vishton et al., 2010; Zago et al., 2004, 2005). The use of 1g acceleration in those studies has been to demonstrate and evaluate any internal model of gravity, but it implies that the model is developed for a drag-free environment, which is highly unlikely to ever be experienced. Baurès, Benguigui, Amorim, & Siegler (2007) argue strongly against an internal model of gravity based, partially, on such an argument, but broad tuning of the model is implied by the imperfect acquisition of visual information for the model which consequently allows only approximate answers (Zago et al., 2008) i.e. a variety of observed accelerations must be tolerated by the model. A range of tolerances is also necessary to account for environmental effects (such as air pressure and wind) and different target densities and shapes that will all affect the acceleration profiles of different objects. The amplitude aspects of any internal model of gravity, however, have never been systematically explored. This study is the first to investigate the breadth of the internal model of gravity's amplitude of acceleration tuning.

We used the experimental design described in Chapter 2 but modified the stimulus targets. Targets now always began at the top of a large projection screen and always descended vertically from stationary at a range of accelerations: 50%, 75%, 90%, 95-105% [in 1% increments] and 110% of g (9.81m/s^2).

Our aims for this experiment were to:

- Investigate whether there is an internal forward model of g.
- Explore its amplitude tuning/characteristics.

Our working hypotheses were:

- That there is an internal model of gravity (see Chapters 1 & 2).
- That it is directionally tuned towards vertically downwards (see Chapter 2).

- That its amplitude is tuned towards slightly less than *g*, so that tracking error increases with increasing deviation from an acceleration that is slightly less than $9.81 m/s^2$.

3.2 Methods

3.2.1 Participants

Nineteen subjects participated in all conditions but several were excluded from each group for behavioural reasons (such as failure to follow instructions) leaving 17 subjects (7 male, 10 female, mean age ± SD: 28.6 ± 4.3) in the laser condition, 13 subjects (6 male, 7 female, mean age ± SD: 27.8 ± 3.9) in the manual condition, and the same 9 whose gaze was studied under all conditions. They reported normal or corrected to normal vision (using contact lenses), no neurological or sensorimotor disorders and gave informed consent prior to participation. Hand dominance was determined using the Edinburgh Handedness Inventory (Oldfield, 1971). The local ethics committee approved experimental procedures.

3.2.2 Experimental setup & task

The experimental setup and task were the same as described in Chapter 2 except that in this experiment target acceleration amplitude rather than direction was varied.

3.2.3 Stimulus videos

Production of stimulus videos was the same as described in Chapter 2, but all targets descended vertically and 15 rates of target acceleration were produced (50%, 75%, 90%, 95-105% [in 1% increments] and 110% of *g* ($9.81 m/s^2$) [for succinctness these amplitudes are also referred to as g50, g75, g90, g95, g95-105 and g110]) using Equation 2-1 in Chapter 2 Methods 2.2.5. The distance available to travel (see Chapter 2 Methods 2.2.3) was identical for each target acceleration meaning that the number of frames in which the target was visible differed with each acceleration for both the stimulus frequency (60 Hz) and the analysed frequency (100 Hz) over the same time (Table 3-1).

Table 3-1. The number of frames in which the target at 60 Hz (stimulus presentation frequency) and 100 Hz (sampling frequency).

g %	a (m/s^2)	Final video frame (60Hz)	Travel (mm)	Final video frame (100Hz)	Travel (mm)	Travel Difference (mm)
50	4.91	62	2534.93	102	2501.80	33.14
75	7.36	50	2453.52	84	2534.29	-80.77
90	8.83	46	2483.16	77	2549.82	-66.66
95	9.32	45	2505.91	74	2483.18	22.73
96	9.42	45	2532.29	74	2509.32	22.97
97	9.52	44	2443.68	74	2535.46	-91.77
98	9.61	44	2468.88	73	2491.90	-23.02
99	9.71	44	2494.07	73	2517.32	-23.25
100	9.81	44	2519.26	73	2542.75	-23.49
101	9.91	44	2544.46	72	2497.34	47.12
102	10.01	43	2451.52	72	2522.06	-70.54
103	10.10	43	2475.55	72	2546.79	-71.24
104	10.20	43	2499.59	71	2499.59	0.00
105	10.30	43	2523.62	71	2523.62	0.00
110	10.79	42	2519.40	69	2494.88	24.52

3.2.4 Protocol

The protocol was the same as described in Chapter 2 but angle conditions became amplitude conditions.

3.2.5 Data processing – marker & gaze

Marker and gaze data processing (including gaze calibration and gaze vector calculation methods) were the same as described in Chapter 2. Serious failure to track markers or participants' failure to follow instructions resulted in the exclusion from analysis of 6 of 855 laser tracks, 270 of 855 manual tracks (270 from the exclusion of 6 participants) and 962 of 2430 (945 from the exclusion of 7 participants) gaze tracks being excluded. Details of exclusion criteria and rates can be found in Appendix 7.4.

3.2.6 Assessing tracking performance

N.B. See the inside back cover for a pullout describing the errors in terms of direction and sign for this experiment.

The number of frames from the 'go signal' (target turned green) to the disappearance of the target behind the occluding block varied depending on acceleration amplitude (Table 3-1). To maintain consistency, only the first 69 samples (690 ms) were analysed for each acceleration condition; any additional samples were discarded. This was the maximum possible time period available for the fastest acceleration used (110% of *g* – see Table 3-1). This resulted in different target travel distance for each condition (Table

3-2 & Figure 3-1). This represents only a small loss of 4 samples compared to the data sets obtained at true *g* (Chapter 2 in which all trials consisted of 730 ms or 73 samples).

Table 3-2. Travel times and distance in video frames (60 Hz), recorded samples (100 Hz) and analysed time frame (690 ms / 69 samples) for differently accelerating targets.

g %	a (m/s^2)	Final video frame (60Hz)	Travel (mm)	Final video frame (100Hz)	Travel (mm)	Travel Difference (mm)
50	4.91	42	1145.18	69	1134.04	11.15
75	7.36	42	1717.77	69	1701.05	16.72
90	8.83	42	2061.33	69	2041.26	20.06
95	9.32	42	2175.84	69	2154.67	21.18
96	9.42	42	2198.75	69	2177.35	21.40
97	9.52	42	2221.65	69	2200.03	21.62
98	9.61	42	2244.56	69	2222.71	21.84
99	9.71	42	2267.46	69	2245.39	22.07
100	9.81	42	2290.36	69	2268.07	22.29
101	9.91	42	2313.27	69	2290.75	22.51
102	10.01	42	2336.17	69	2313.43	22.74
103	10.10	42	2359.07	69	2336.11	22.96
104	10.20	42	2381.98	69	2358.79	23.18
105	10.30	42	2404.88	69	2381.48	23.41
110	10.79	42	2519.40	69	2494.88	24.52

Tracking performance was assessed as described in the direction experiment (Chapter 2) with three differences:

- Only in-line errors (parallel to target trajectory i.e. vertical) were statistically analysed and scrutinised because unlike in Chapter 2 there was no sideways component to target movement.
- To allow comparison of performance across amplitude conditions I analysed from the 'go signal' to the lowest number of samples available any condition (69 frames at 100 Hz for 110% of g) for all conditions, which gives 690 ms of tracking time (only 40 ms less than in Chapter 2). See Figure 3-1 for travel distance and travel time for each target acceleration.

Consequently there were 3 measures for every trial (total position, velocity and acceleration error).

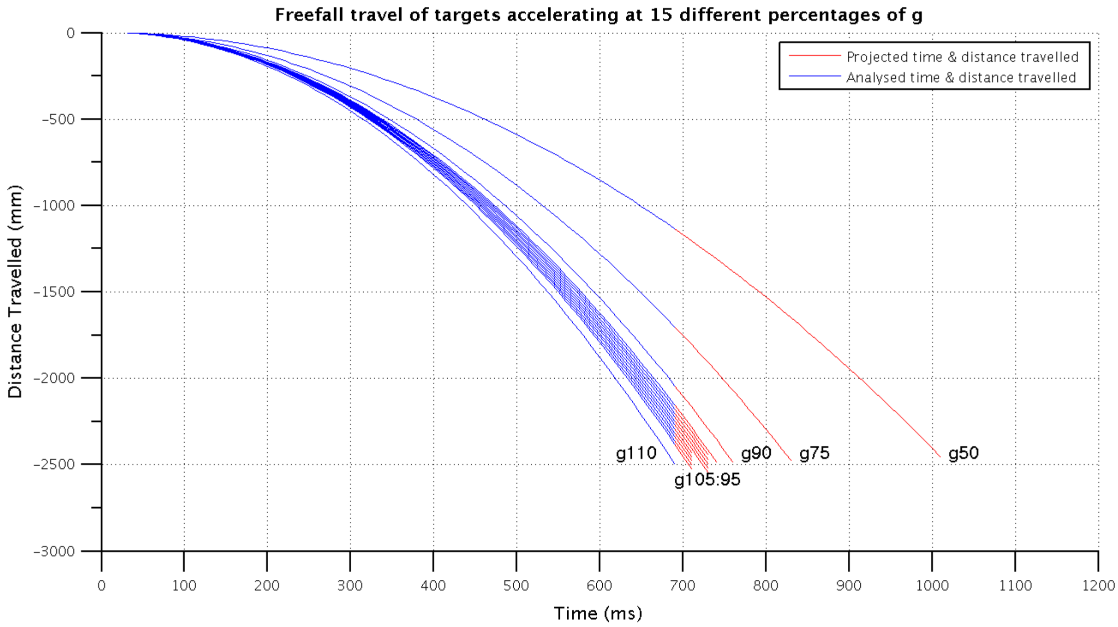


Figure 3-1. Freefall travel of targets accelerating at different 15 percentages of g.

3.2.7 Statistical analysis

Two factor repeated measures ANOVAs were run on all measures. As in Chapter 2 the tracking output was found to differ highly significantly (p < .001) between tracking conditions (see Results 3.3.1) so in this study tracking methods were also analysed separately. Type IV Sums of Squares corrected for sphericity and where violated (as indicated by Mauchly's Test of Sphericity) a conservative Greenhouse-Geisser (GG) correction was employed in the interaction effects and where this was non-significant a less conservative Huynh-Feldt (HF) correction was examined. Where sphericity could not be assessed, corrected (Greenhouse-Geisser and Huynh-Feldt) and uncorrected degrees of freedom and significance values are reported.

Missing data was handled in the same way as in Chapter 2 (Chapter 2 Results 2.2.9). See Appendix 7.4 for exclusion rates.

We had specific hypotheses relating to change in error with practice and differences between acceleration amplitude conditions. Pairwise comparisons were conducted but are not reported for those reasons. The effects within each ANOVA were examined using planned comparisons contrasts:

- Simple (first) contrasts for the effect of amplitude: every acceleration amplitude was compared to g100.

- Repeated contrasts for the effect of attempt: every attempt was compared to its successor i.e. attempt 1 compared to attempt 2, and attempt 2 compared to attempt 3.

In order to identify any amplitude-attempt interaction, simple and repeated contrasts were combined: the difference between an attempt and its successor (repeated contrast component) at every amplitude was compared to the same number attempt and its successor at g100 (simple contrast component). e.g. the difference from attempt 1 to attempt 2 at g50 was compared to the difference from attempt 1 to attempt 2 at g100.

3.2.8 Mode of manual tracking

The mode of manual tracking was investigated and discussed in Chapter 2 with the conclusion that a vector from the dominant eye to the screen plane via the pointing index fingertip is the vector used when pointing. This vector was therefore again used for analysis of manual tracking in the current study.

3.3 Results

3.3.1 Main effects on tracking error

In Chapter 2 main effects of trajectory direction, tracking method and attempt number on total position error were significant ($p<.001$). A full factor, type III SS univariate ANOVA examined such effects in the current study but with trajectory direction substituted by acceleration amplitude.

All main effects were significant: acceleration amplitude ($F(14,3194)=4.9$, $p<.001$), method of tracking ($F(2,2564)=657.48$, $p<.001$), and repetition ($F(2,2564)=31.03$, $p<.001$). Significant interaction effects were for amplitude*attempt ($F(28,2564)=1.67$, $p<.001$) and mode*attempt ($F(4, 2564)=8.54$, $p<.001$); see Figure 3-2.

One-way ANOVAs were used to examine differences between total position errors for acceleration amplitude, tracking method (manual tracking, laser tracking or all pooled gaze tracking) and gaze tracking method (in the manual and laser conditions and in isolation). Levene's test revealed a significant ($p<.001$) violation of homogeneity of variance for each ANOVA. Games-Howell post-hoc tests were employed to examine where differences between groups lay. Games-Howell tests are accurate when sample sizes and sample variances are unequal (Field, 2009: pages 374-375).

Total position error was significantly affected by acceleration amplitude ($F(14,2564)=4.21$, $p<.001$). Games-Howell tests revealed that tracking error at 50% of *g* differed significantly ($p<.05$) from all other errors apart from at 75% of *g*, and tracking at 75% of *g* differed significantly ($p<.05$) from tracking at 110% of *g* (Figure 3-2D).

Total position error was significantly affected by main tracking method ($F(2, 2564) = 623.53$, $p < .001$). Games-Howell post-hoc test revealed laser and gaze tracking to differ significantly from manual tracking ($p < .001$) but not from one another (Figure 3-2E).

Total position error was significantly affected by the method of gaze tracking ($F(2, 1214) = 69.52$, $p < .001$). Games-Howell post-hoc test revealed all tracking methods to differ significantly from one another ($p < .001$) (Figure 3-3).

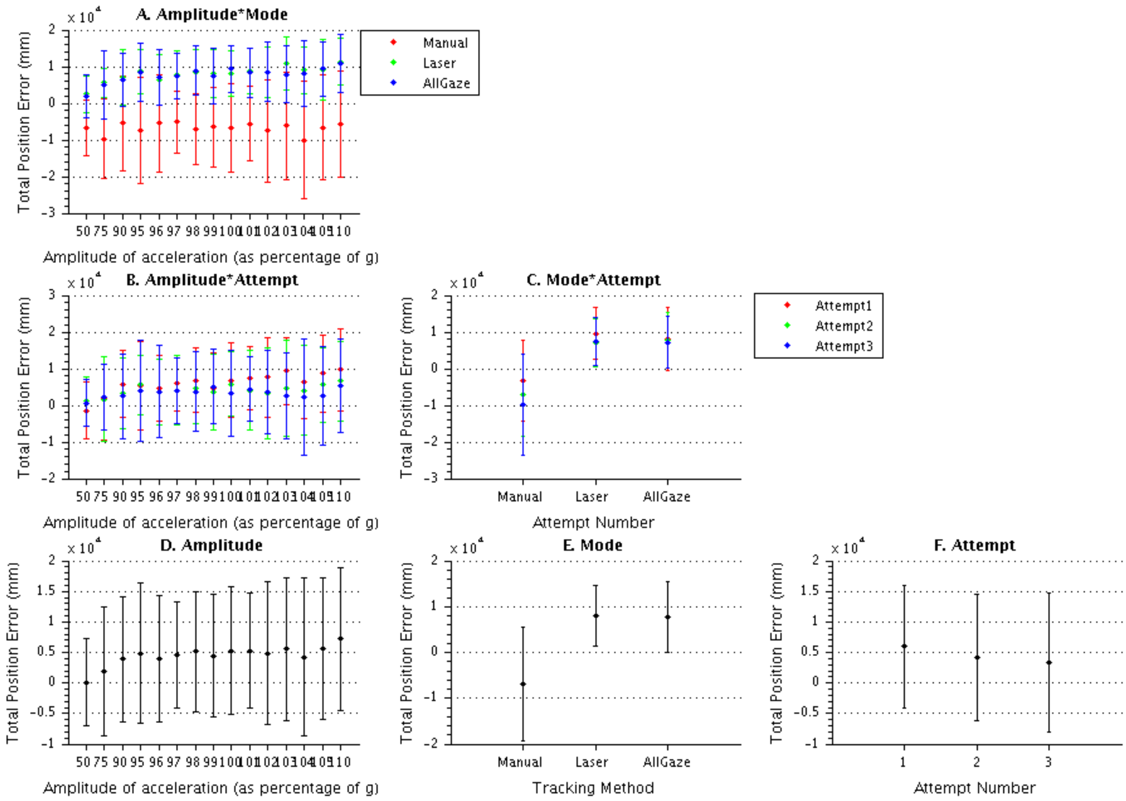


Figure 3-2. Mean and SD of total position error for the main factors of target acceleration amplitude (D), mode of tracing (E) and attempt number (F) with interactions (A,B&C). All tracking angles and attempts are included.

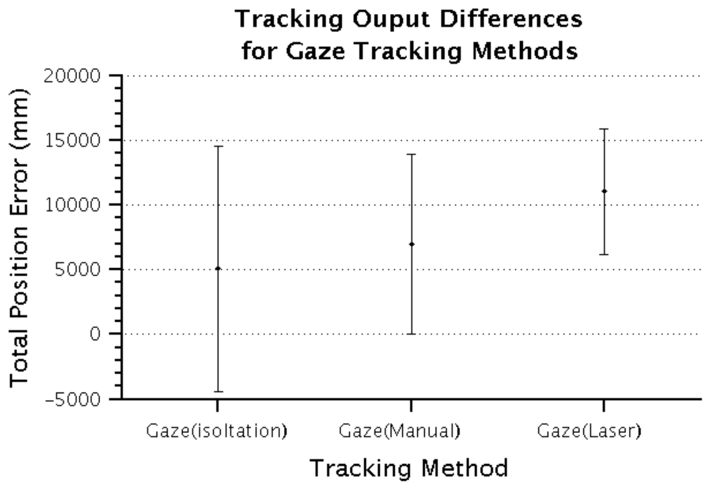


Figure 3-3. Mean and SD of total position error for each tracking method. All tracking angles and attempts are included. A: Manual tracking, laser tracking and all gaze tracking. B: Gaze tracking in each condition i.e. in isolation, with manual tracking or with laser tracking.

Each main factor (acceleration amplitude, tracking method and repetition) significantly affected tracking output. Tracking method is the main condition difference from where differences in tracking amplitude and repetition can emerge. As such each tracking method was separately examined for the effect of target acceleration amplitude, repetition number and the interaction of these two.

3.3.2 Manual tracking

3.3.2.1 Manual tracking: Time series of tracked position, velocity and acceleration averaged across target acceleration amplitudes

There are several clear features in Figure 3-4:

1. All tracking was ahead of (below) the target centre by between approximately 40-80 mm at the start of tracking (initial negative error) meaning that at this time tracking was in the lower half of the target sphere (target radius was 75 mm).
2. Tracking error changed gradually from its initial negative value becoming positive during a reaction time in which the stationary pointing finger lagged behind (above) the falling target. Tracking accelerated more slowly than the target up to approximately 150-175 ms from where it accelerated more quickly than the target and peaked at ~300 ms after which the tracked position caught up with and then moved increasingly ahead of the target. In tracking attempts 2 and 3 the time of this movement was ~50 ms earlier than at attempt 1 and the greatest distance behind the target decreased.

3. There appears to be a single movement indicated by a sharp negative spike in acceleration at ~300 ms which corresponds to the clear change in tracking from typically behind the target to ahead of it. At the end of the analysed time frame there appears to be an increase in acceleration that may have developed into a second movement phase if sufficient time was available.
4. In all measures the positive peak errors decrease with practice whereas the peak negative errors increase for the position and acceleration measures indicating a preference to track on or ahead of the target.

These plots suggest that tracking was not coordinated to persistently be ahead of the target by maintaining steady acceleration, but rather a movement was executed and evaluated before the next was generated.

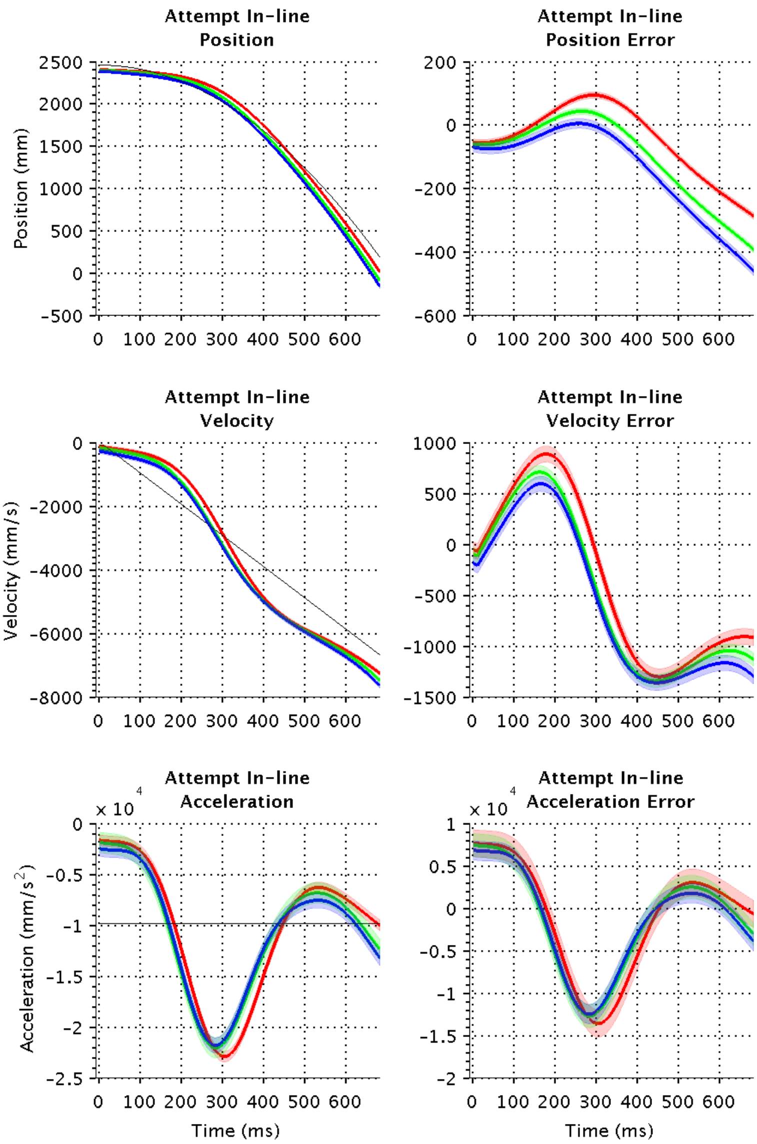


Figure 3-4. Time series of manual tracked in-line position, velocity and acceleration for each attempt. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

3.3.2.2 Manual tracking: Time series of tracked position error for each target acceleration amplitude

There are several clear features in Figure 3-5:

1. All tracking was ahead of (below) the target centre by between approximately 40-80 mm at the start of tracking (initial negative error). The target's radius was 75 mm meaning that tracking in every amplitude condition was in its lower half (as suggested by the attempt time series Figure 3-4).
2. During a reaction time the error decreased gradually from its initial negative value and for accelerations >50% of *g* the error then increased in positive values (tracking behind the target) whereas at 50% of *g* the error remained extremely small and negative (slightly ahead of the target).
3. At ~300 ms on the first attempt, tracking began to move ahead of the target (or further ahead for g50) and remained ahead. The timing of this catch-up and the peak positive error both decreased with practice (N.B. peak positive error could become minimum negative error e.g. from the second to the third attempt at g110) whereas the final error tended to increase with practice.

These plots indicate a single tracking movement initiated at ~300 ms, and that tracking was coordinated to be ahead of the target not by maintaining steady acceleration but rather by generating this movement following a visual reaction time i.e. once the participant had seen that the target had begun to move.

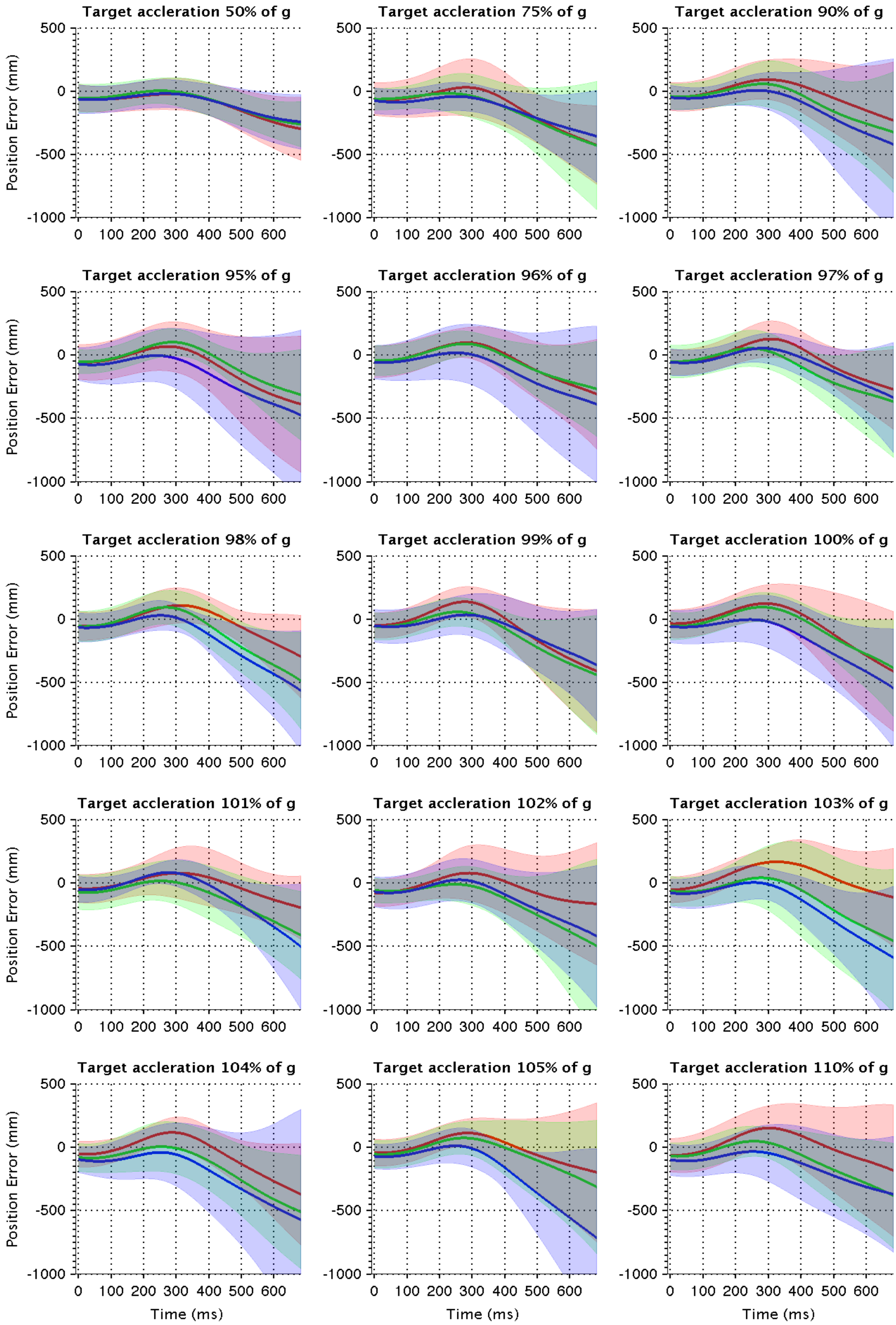


Figure 3-5. Time series of manual tracked in-line position, velocity and acceleration for each acceleration amplitude condition. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

3.3.2.3 Manual tracking: The effect of target acceleration amplitude on the in-line component of tracking

Total position error was not significantly affected by target acceleration. Tracking was always ahead of the target overall (Figure 3-6). Target acceleration did not affect the total distance ahead summed over the track but error SD increased as acceleration amplitude increased.

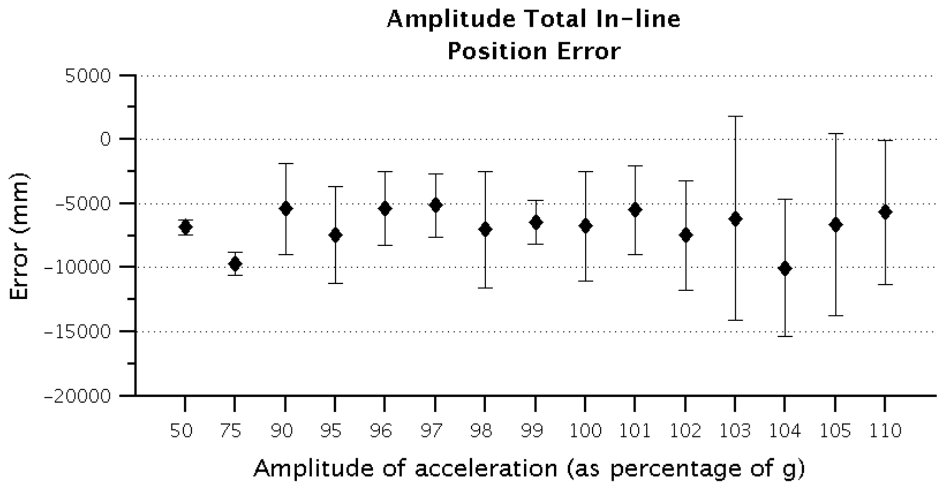


Figure 3-6. Manual tracking total in-line position error means and SD at target acceleration amplitude.

Total velocity and acceleration errors were not significantly affected by target acceleration. All velocities and accelerations were greater than the target's. As target acceleration increased, the mean velocity error increased in a weak (non significant) negative trend (tracking became increasingly faster than the target as the target's acceleration increased) and the SD typically increased. The smallest acceleration error was for the slowest accelerating target and errors increased (but not significantly) from that acceleration to 97% of *g* though following this there was no clear pattern. Large differences between attempt errors within amplitudes (Results 3.3.2.5) appear to be the cause of the lack of any significant pattern.

Manual tracking was ahead of, and faster than, the target. There was a weak negative trend to velocity and acceleration data meaning that tracking became increasingly faster than the target as target acceleration increased. The SD typically also increased with increasing target acceleration.

3.3.2.4 Manual tracking: The effect of repetition (attempt no.) on the in-line component of tracking

Total position ($F(2,24)=12.055$, $p<.001$) and velocity errors ($F(1.401,16.817)=4.419$,

p=.04) were significantly affected by attempt number. In both cases contrasts revealed that attempt 1 was significantly different from attempt 2 (position: $F(1,12)=12.047$, p=.005; velocity: $F(1,12)=6.835$, p=.023).

Tracking became increasingly further ahead of and faster than the target at each subsequent attempt (i.e. error increased) (Figure 3-7). There was a clear negative trend for acceleration error means but large SDs meant there were no significant differences.

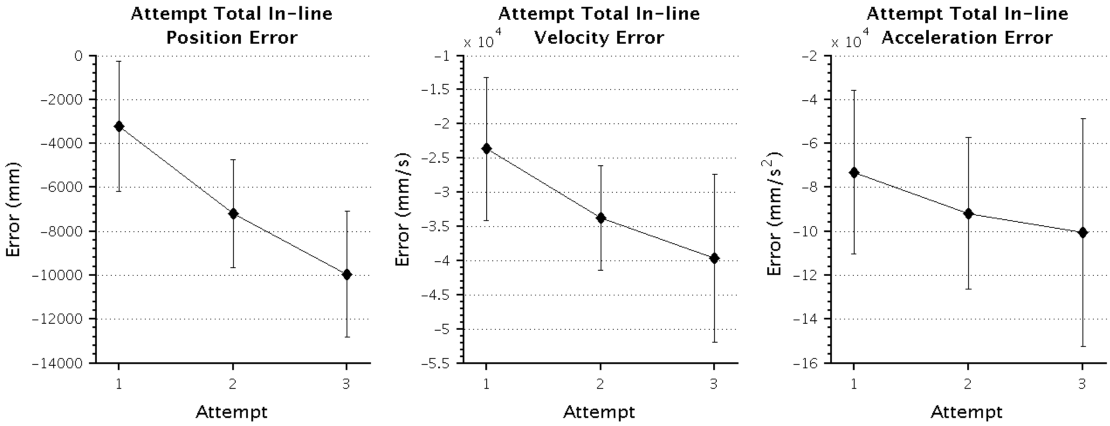


Figure 3-7. Manual tracking total in-line position, velocity and acceleration error means and SD at tracking attempts.

Tracking was ahead of the target, faster than it and moved further ahead and faster still at each attempt.

3.3.2.5 Manual tracking: Amplitude-attempt interaction on the in-line component of tracking

For total position error there may have been a significant interaction (see Methods 3.2.7) between target acceleration and attempt number (uncorrected $F(28,336)=1.807$, p=.008; GG $F(6.527,78.336)=1.807$, p=.102; HF $F(15.139,181.668)=1.807$, p=.036). Contrasts revealed a significant difference between attempt 1 and attempt 2 from g100 to g110 error ($F(1,12)=6.646$, p=.024) and between attempt 2 and attempt 3 from g100 to: g50 error ($F(1,12)=5.121$, p=.043); g97 error ($F(1,12)=6.646$, p=.024); g99 error ($F(1,12)=8.202$, p=.014); and g101 error ($F(1,12)=4.882$, p=.047).

Error typically increased with practice as the tracked position moved further ahead of the target (Figure 3-8). The error when tracking accelerations >75% of g typically increased from the first attempt to the second attempt, and at accelerations >102% of g the error increased again at the third attempt. There was very little change between attempt errors when the target acceleration was 50% or 75% of g. Note that there is little difference between the attempt errors when tracking at 99% of g. The increased SDs as the target acceleration amplitude increases (Results 3.3.2.3) is the result of increases in the differences (representing an increase in error) between each subsequent attempt within those higher acceleration conditions.

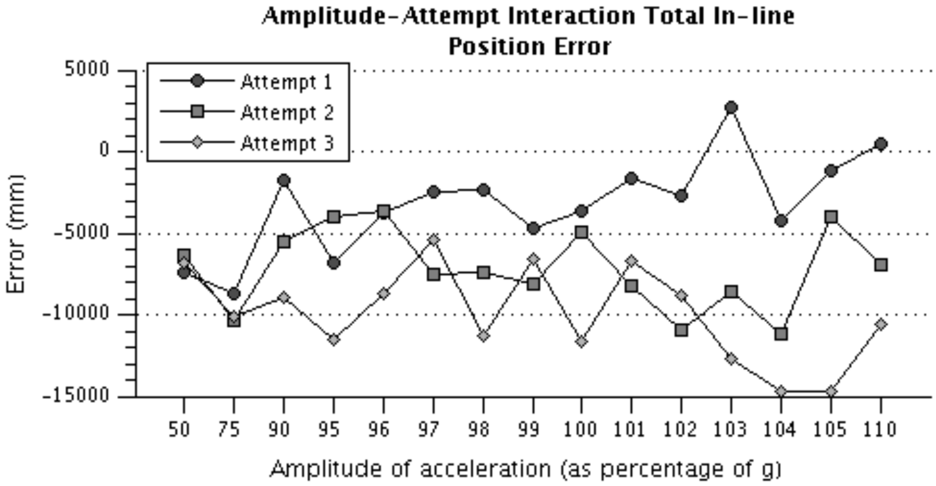


Figure 3-8. Manual tracking total in-line position attempt error means at target acceleration amplitude.

For total velocity error there may have been a significant interaction between target acceleration and attempt number (uncorrected $F(28,336)=1.765$, $p=.011$; GG $F(6.683,80.201)=1.765$, $p=.109$; HF $F(15.966,191.591)=1.765$, $p=.039$). Contrasts revealed a significant difference between attempt 1 and attempt 2 from g100 error to g110 error ($F(1,12)=11.325$, $p=.006$) and between attempt 2 and attempt 3 from g100 error to g110 error ($F(1,12)=7.056$, $p=.021$).

Tracking was always faster than the target (Figure 3-9). Considering only the second and third attempts, there is a negative trend to velocity error from 50-104% of *g*. The difference in attempt means is small up to 101% of *g*, beyond which there is a large increase in velocity from the first to the second and third attempt. This may indicate an expectation at the first attempt that the target would travel more slowly than it did, and if so this indicates some aspect of modelling because this was not found for accelerations <100% of *g*. Also, there is rapid adaptation for the second attempt given a perceived error in the first attempt.

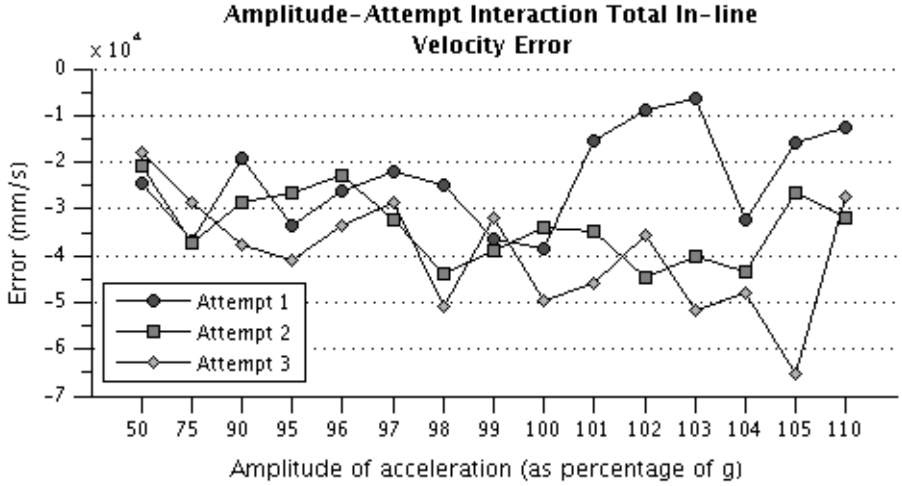


Figure 3-9. Manual tracking total in-line velocity attempt error means at target acceleration amplitude.

For total acceleration error there was no significant interaction between target acceleration and attempt number (uncorrected *F*(28,336)=.815, *p*=.737; GG *F*(5.925,71.097)=.815, *p*=.561; HF *F*(12.349,148.183)=.815, *p*=.638).

Tracking acceleration was always greater than the target's acceleration (Figure 3-10). There was little variation of attempt means within acceleration values up to 100% of *g* from where there was more variation (except tracking at 104% of *g*). For accelerations up to 100% of *g* the tracking acceleration increased as target acceleration increased. As with the total velocity error it may be important that the within amplitude errors are similar up to 100% of *g*, but beyond this those errors are more variable. I suggest in Discussion (3.4.5) that this might indicate a general inability to accurately track falling targets accelerating faster than naturally possible.

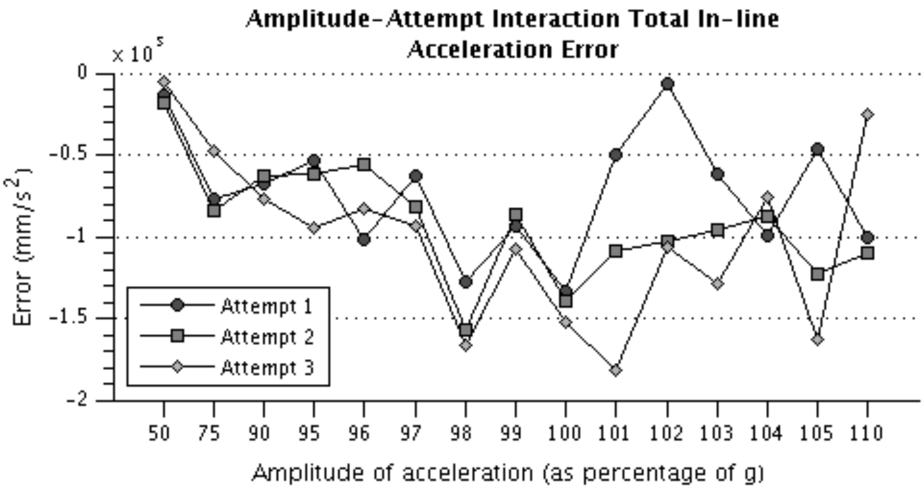


Figure 3-10. Manual tracking total in-line acceleration attempt error means at target acceleration amplitude.

Section Summary

Error typically increased from the first to the second attempt when targets accelerate faster than *g*. The onset of more variable attempt errors within amplitude conditions at accelerations greater than 100% of *g* suggests amplitude tuning in a predictive model of target motion. The tuning appears tolerant to amplitudes of less than *g* but at accelerations greater than *g* tracking performance abruptly changes. I suggest in Discussion that these error patterns therefore indicate a mechanism developed in accordance with real world experience.

3.3.3 Laser tracking

3.3.3.1 Laser tracking: Time series of tracked position, velocity and acceleration averaged across target acceleration amplitudes

There are several interesting features in the laser attempt time series (Figure 3-11):

- There was a small downwards drift of the laser tracking spot from the start of the analysed time frame i.e. before any reaction time following start of target movement. This drift presumably represents anticipation because subjects knew in this experiment that the target was going to move vertically downwards. This non-zero velocity makes it difficult to identify the start of tracking proper after the visual reaction time, but this appears to be around 150 ms after the target began to move at time zero. Tracked position nevertheless fell increasingly behind up to a maximum positive error at ~300 ms. Following this, at approximately 350 ms the tracking velocity caught up with and matched the velocity that would have resulted under acceleration at *g*, but from 500 ms onwards, tracking velocity fell progressively behind what would be required for tracking a target accelerating at *g*.
- With practice the position error peak reduced and it occurred ~50 ms later with practice (when manual tracking it occurred 50 ms *earlier*).
- Position error following a single presentation decreased which appears to be a result of slightly greater anticipatory drift at the start of each trial in the second and third attempts than at the first attempt.
- Following the positive peak in position error there was a reduction in that error representing tracking gaining on the target, though it failed to reach the target and the error subsequently again increased positively (falling further behind) from ~500 ms to the end of tracking. The negative acceleration spike (approximately 250-300 ms) caused tracked velocity to increase and become briefly a little faster than the target's velocity. This achieved the temporary reduction in positive position error.

As in the manual tracking condition, there is evidence when laser pointing for a single tracking movement that occurred following an initial reaction time; but unlike the manual condition there is no suggestion of a second movement developing at the end of the analysed time period.

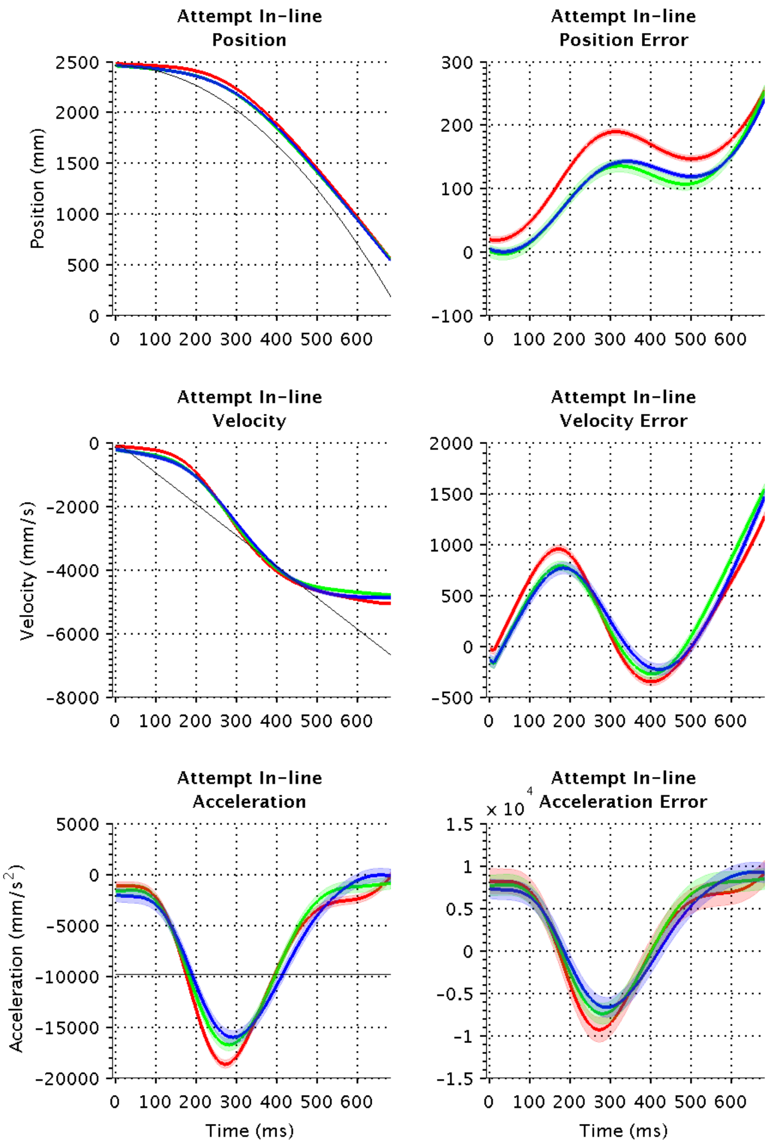


Figure 3-11. Time series of laser tracked in-line position, velocity and acceleration for each attempt. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

3.3.3.2 Laser tracking: Time series of tracked position error for each target acceleration amplitude

Many of the features indentified in the attempt time series are visible in each acceleration amplitude time series (Figure 3-12):

- Tracking initially fell behind the target to a maximum at ~300 ms.

- This error peak typically reduced with practice, though any change in spike timing spike was rather variable.
- Following this maximum, position error typically decreased before increasing for the remainder of the trial.
- Unlike the manual tracking condition there was a clear difference in position error between the amplitude conditions: tracking became further behind as the target acceleration increased.

Unlike the manual tracking condition there was a clear difference in position error between the amplitude conditions: tracking became further behind as the target acceleration increased.

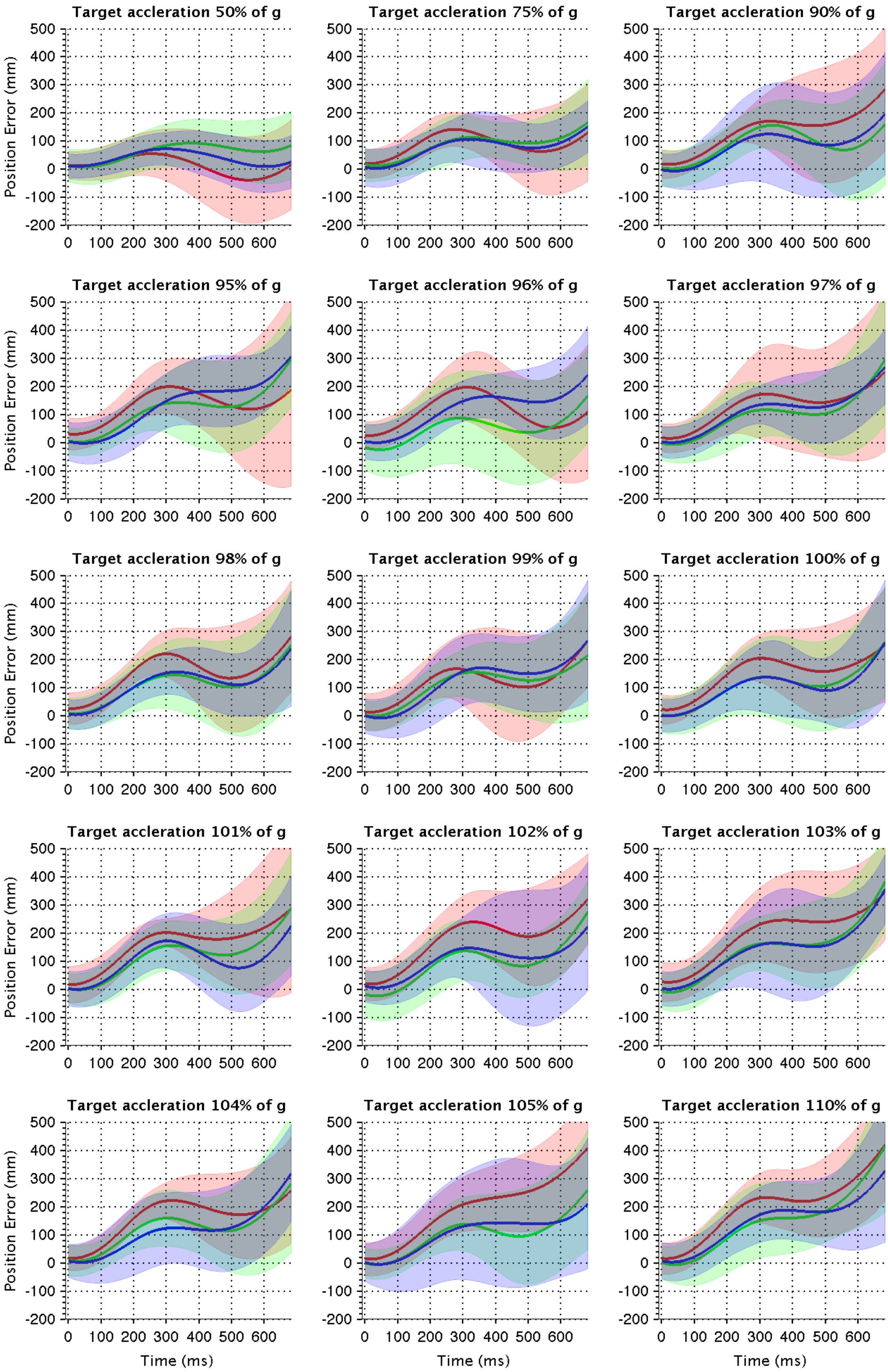


Figure 3-12. Time series of laser tracked in-line position, velocity and acceleration for each acceleration amplitude condition. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

3.3.3.3 Laser tracking: The effect of target acceleration amplitude on the in-line component of tracking

Total position error was significantly affected by target acceleration ($F(14,224)=7.445$, $p<.001$). Contrasts revealed significant differences between g100 error and: g50 error ($F(1,16)=26.107$, $p=.001$); g75 error ($F(1,16)=11.762$, $p=.003$); g103 error ($F(1,16)=6.735$, $p=.023$); and g110 error ($F(1,16)=16.625$, $p=.001$).

Tracking in every condition was behind the target overall, and the error increased as target acceleration increased (a positive gradient, Figure 3-13). Linear regression (Figure 3-14) confirms that relationship ($r^2=.838$, $F(1,16)=67.471$, $p<.001$). This contrasts with the manual tracking where all errors were negative and did not vary significantly. The SD of error when tracking a target acceleration 99% of *g* was much smaller than at any other acceleration amplitude - I suggest in Discussion 3.4.6 that a model of gravity is tuned to this value. Also, I suggest that because tracking fell increasingly far behind, tracking was not entirely predictive but rather was based at least partly on comparison of the immediate tracked position with the immediate target position.

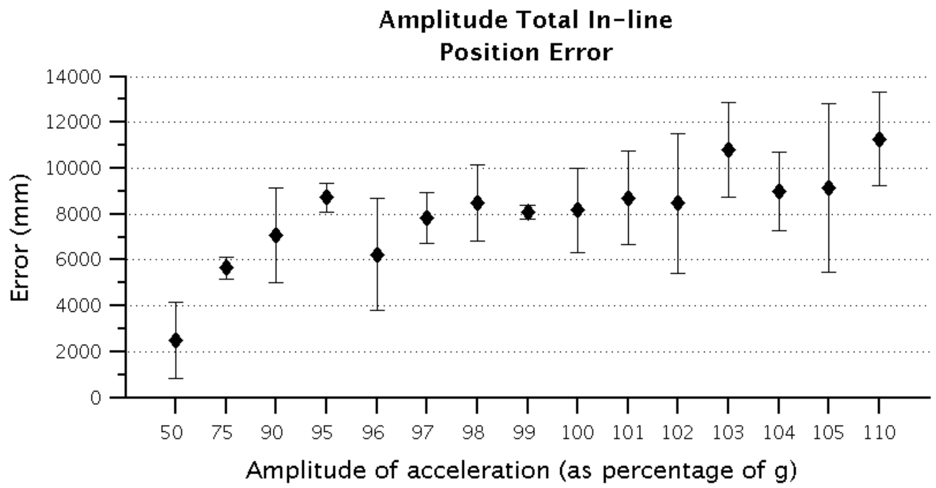


Figure 3-13. Laser tracking total in-line position error means and SD at target acceleration amplitude.

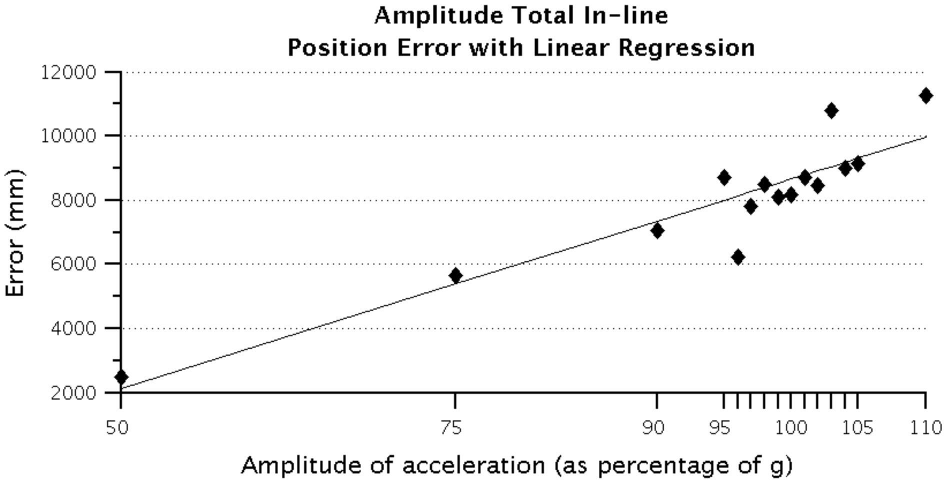


Figure 3-14. Laser tracking total in-line position error means at target acceleration amplitude linear regression.

Total velocity error was significantly affected by target acceleration ($F(14,224)=9.067$, $p<.001$). Contrasts revealed significant differences between g100 error and: g50 error ($F(1,16)=$, $p<.001$); g75 error ($F(1,16)=16.748$, $p=.001$); g96 error ($F(1,16)=5.22$, $p=.036$); g103 error ($F(1, 16)=8.503$, $p=.01$); and g110 error ($F(1,16)=10.585$, $p=.005$).

Tracking was slower than the target, and the amount slower increased as acceleration amplitude increased (Figure 3-15). As with position error, linear regression (Figure 3-16) shows a strong relationship between velocity error and acceleration amplitude ($r^2=.833$, $F(1,16)=65.006$, $p=<001$). Tracking variability was the least when targets accelerated at 98% of *g*.

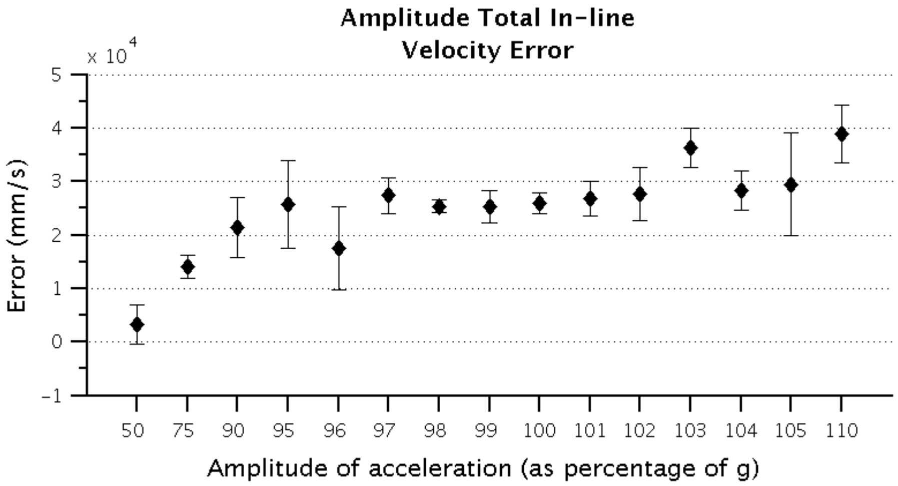


Figure 3-15. Laser tracking total in-line velocity error means and SD at target acceleration amplitude.

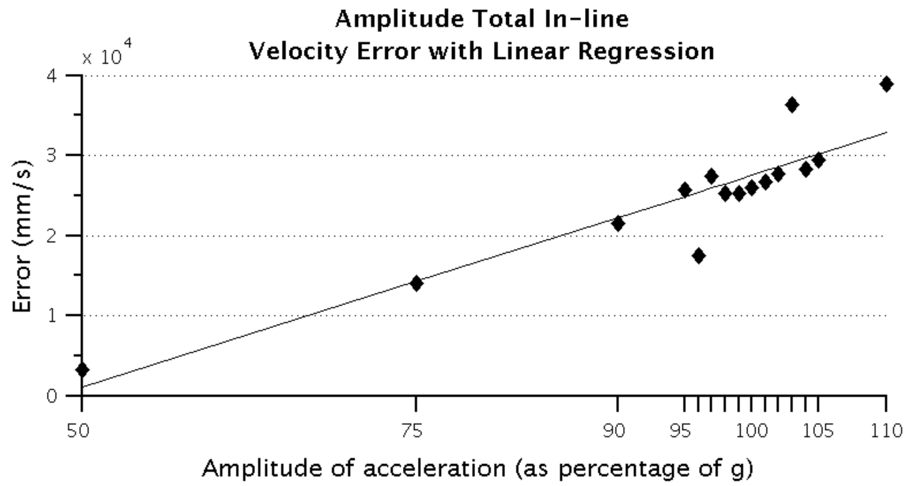


Figure 3-16. Laser tracking total in-line velocity error means at target acceleration amplitude linear regression.

Total acceleration error was significantly affected by target acceleration (GG $F(5.646,90.338)=4.602$, $p<.001$). Contrasts revealed significant differences between g100 error and: g50 error ($F(1,16)=55.859$, $p<.001$); and g75 error ($F(1,16)=20.503$, $p<.001$).

Tracking did not accelerate as fast as the target in any condition. Tracked acceleration error increased the faster the target accelerated (Figure 3-17) just as in the position and velocity plots.

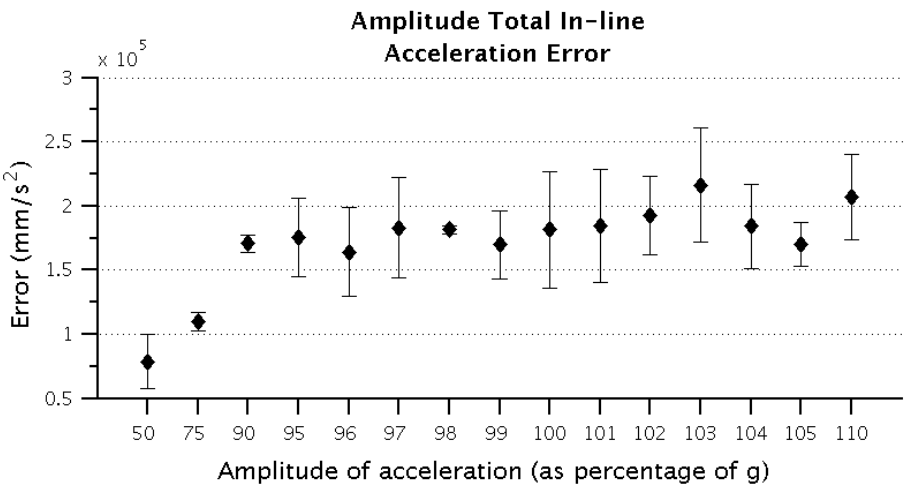


Figure 3-17. Laser tracking total in-line acceleration error means and SD at target acceleration amplitude.

Section Summary

In all measures laser tracking was behind/slower than the target, and tracking errors increased with positive gradients as the target acceleration increased. Manual tracking error (see earlier) also increased with target acceleration but the trend there was to track increasingly further ahead and faster than the target.

In Chapter 2 Discussion 2.4.6 I suggested that laser tracking was behind the target in that study because participants were comparing the feedback of the laser spot to the perceived position of the target in order to manage the tracking output that was informed using a predictive mechanism. In Discussion 3.4.6 I argue that the pattern of laser errors in the current study supports a similar conclusion.

3.3.3.4 Laser tracking: The effect of repetition (attempt no.) on the in-line component of tracking

Total position error ($F(2,32)=12.207$, $p<.001$) and total acceleration error ($F(2,32)=9.721$, $p=.001$) were significantly affected by attempt number. In both cases contrasts revealed that attempt 1 was significantly different from attempt 2 (position: $F(1,16)=19.353$, $p<.001$; acceleration: $F(1,16)=16.614$, $p=.001$).

The results are mixed in that there is a reduction in position error and an increase in acceleration error whilst both are positive meaning that tracking was behind and slower than the target (Figure 3-18).

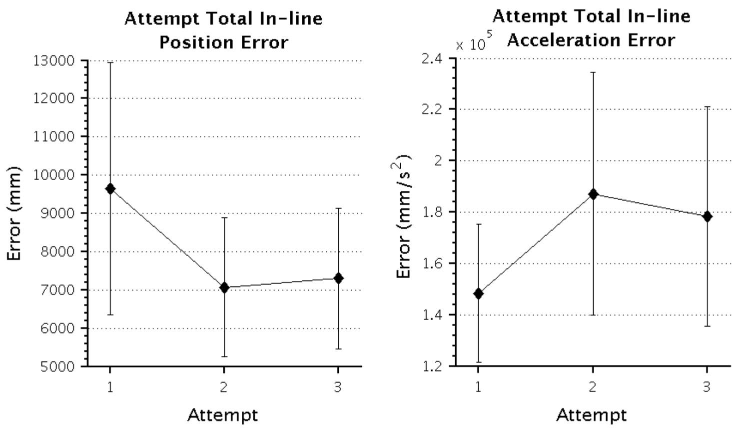


Figure 3-18. Laser tracking total in-line position, velocity and acceleration error means and SD at tracking attempts.

3.3.3.5 Laser tracking: Amplitude-attempt interaction on the in-line component of tracking

For total position error there was no significant interaction between target acceleration and attempt number (uncorrected $F(28,448)=1.313$, $p=.134$; GG $F(9.146,146.343)=1.313$, $p=.234$; HF $F(22.396,358.331)=1.313$, $p=.157$). However contrasts revealed a significant difference between attempt 1 and attempt 2 from g100 error to g50 error ($F(1,16)=14.305$, $p=.002$).

When tracking a target accelerating ≥100% of *g* there was a clear and consistent reduction in error from the first to the second and third attempts (Figure 3-19). This was not present at other amplitudes (except at g90). There was little or no change from the second to the third attempt apart from at g50 and g96. Most second and third attempt errors varied between ~8000 mm and ~10,000 mm and there is no clear increase as the target acceleration increased. However, there is a clear increase in the first attempt errors as the target acceleration increases. Note that there is almost no change at 99% of *g*.

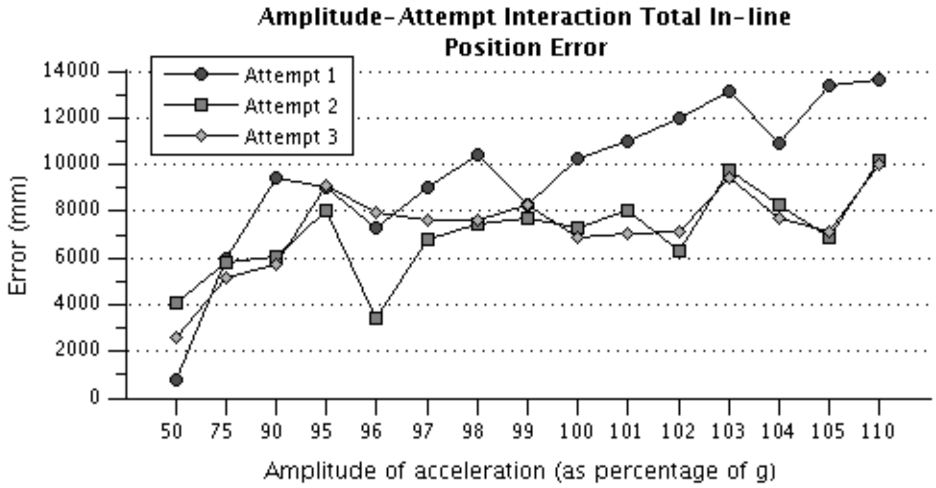


Figure 3-19. Laser tracking total in-line velocity attempt error means at target acceleration amplitude.

There may have been a change in tracking control from the first to subsequent attempts at acceleration amplitudes >100% of *g*; see Discussion 3.4.6. Although tracking was behind the target, the finding that there was so little change in error when tracking a target accelerating at 99% of *g,* compared to much larger changes seen at similar amplitudes just above or below this value, suggests that tracking was tuned to this amplitude and that this did not change with repetition.

3.3.4 Gaze only tracking

3.3.4.1 Gaze only tracking: Time series of tracked position, velocity and acceleration averaged across target acceleration amplitudes

The attempt time series plots (Figure 3-20) show clearly that across all directions and participants:

- Tracking started below the target by 25-40 mm. There is no evidence of anticipation; gaze was stable for ~200 ms, after which gaze began to deflect downwards. As the target began to fall, position error became positive (gaze behind the target) and increased up to a peak at approximately 300 ms. The peak error decreased with practice

- A gaze acceleration (downwards) spike, and related increase in tracking velocity (that became greater than the target's velocity) halted the position error increase.
- At ~400 ms, tracking caught up with the target and for the first and second attempts it overtook the target (negative position error) but the third attempt did not (position error remained positive). But in each case, error reduced to 50 mm or less, meaning that gaze was within the target radius. Gaze acceleration and deceleration were less extreme following practice.
- A second clear downwards gaze acceleration spike at ~500ms causes tracking velocity to increase to almost match target velocity. By this time, tracking is behind the target and the velocity increase only serves to stall an increasing position error.

The timing of the first catch-up saccade matches that of the catch-up movement seen in the laser and manual conditions. An important feature is that, with practice, the acceleration spike at 300 ms reduced in amplitude, which caused the tracked velocity profile to more closely match that of the target's. However, this resulted in tracked position error after 300 ms increasing with practice.

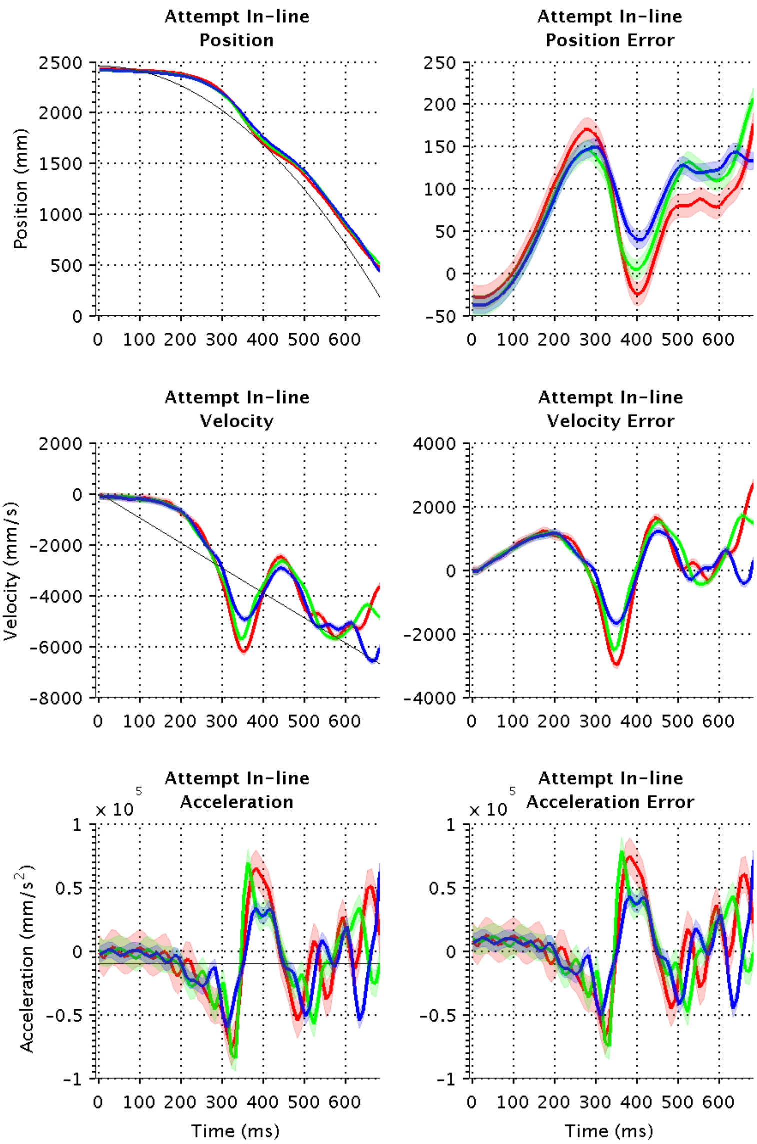


Figure 3-20. Time series of gaze tracked (in the gaze only condition) in-line position, velocity and acceleration for each attempt. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

3.3.4.2 Gaze only tracking: Time series of tracked position error for each target acceleration amplitude

The gaze tracking time series plots were much less clear than in the manual and laser conditions with more inflexions and a large increase in SD (shaded areas) following the first saccade at ~300 ms. In every acceleration condition, tracking started slightly below (ahead of) the target.. Following this the position error increased up to onset of a first saccade at ~300 ms. This saccade time is consistent for all acceleration amplitudes apart from the first attempt when tracking a target accelerating at 50% of *g* where the saccade occurs at ~200 ms. The catch-up saccade reduced tracking error to near zero. .

Beyond the first saccade the error pattern is less clear indicating tracking varied across trials contributed by different individuals. The small wavelets in the plots are probably the result of differences in the timing and amplitudes of further catch-up saccades throughout the trial, though in many plots (e.g. g97, g98, g103, g104) a second catch-up saccade is clear at approximately 500-550 ms where there is a clear downwards deflection in the error (a reduction in lag error).

It is worth noting that for all acceleration amplitudes the tracking error averaged across trials (red, green, blue lines) only rarely, and even then only briefly exceeded 200 mm. Tracking of a target accelerating at 50% of *g* resulted in smaller errors than seen for the other more rapid accelerations; errors were closer to zero, but the SD (variability) was still large. Tracking this target may simply be an easier task due to its low velocity.

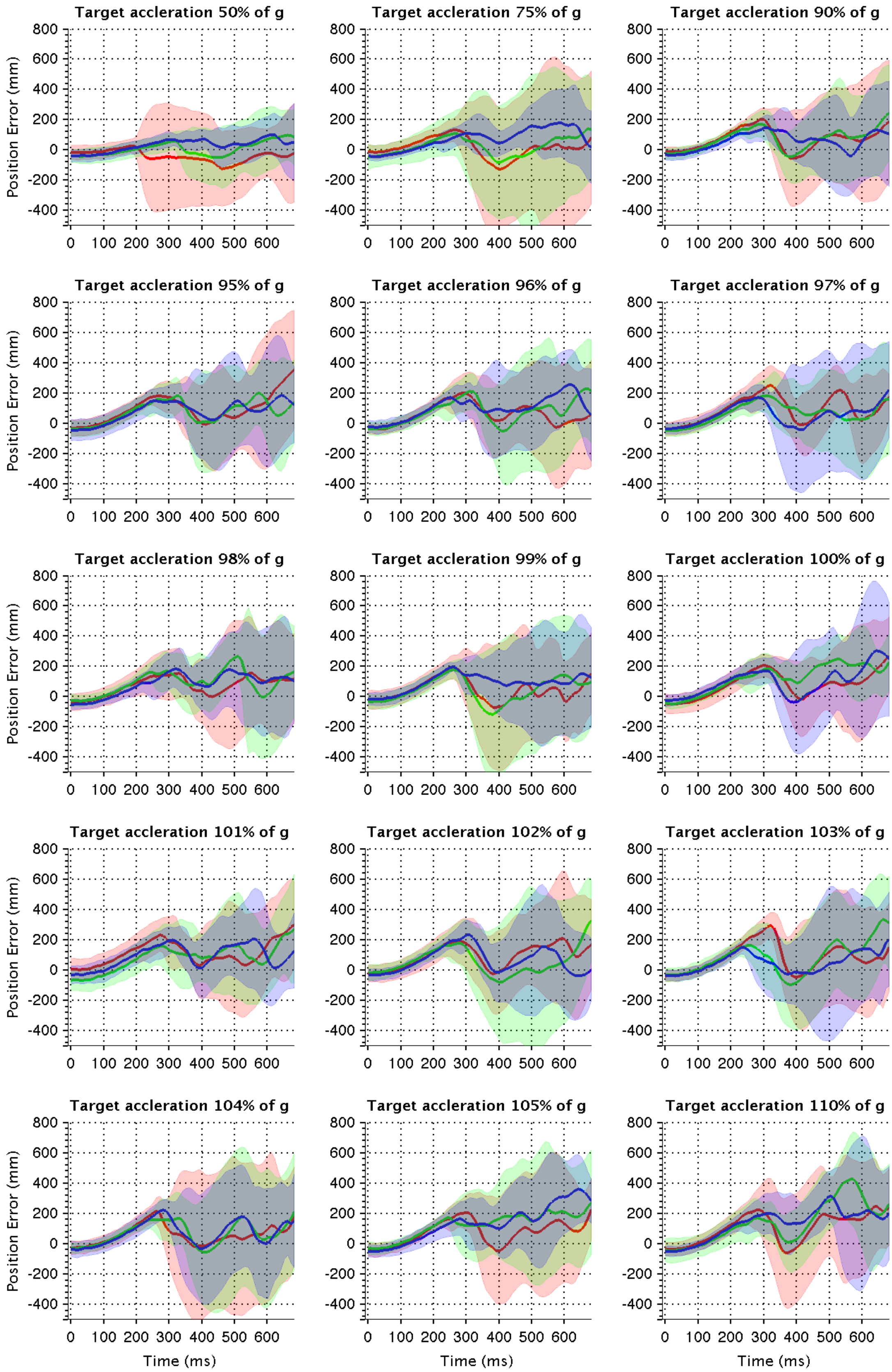


Figure 3-21. Time series of gaze tracked (in the gaze only condition) in-line position, velocity and acceleration for each acceleration amplitude condition. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

3.3.4.3 Gaze only tracking: The effect of target acceleration amplitude on the in-line component of tracking

Total position error was not significantly affected by target acceleration (uncorrected $F(14,112)=1.673$, $p=071$; GG $F(2,884,23.07)=1.673$, $p=.202.$; HF $F(4.682,37.455)=1.673$, $p=.202$). However, contrasts revealed significant differences between g100 error and g50 error ($F(1,8)=37.904$, $p<.001$).

Only when target acceleration was 50% of *g* was tracking ahead of the target and then only by 101.1 mm (Figure 3-22). The distance tracked behind the target tended to increase as the acceleration amplitude increased, and this was close to a linear relationship (Figure 3-23) ($r^2=.757$, $F(1,16)=40$, $p=<.001$). The pattern in Figure 3-22 is similar to that seen in the laser condition though the errors are smaller and the difference from the smallest error to the 'middle' errors (~0 mm at g50 to ~5000 mm at g95:104) is smaller than in the laser condition (~2000 mm at g50 to ~8000 mm at g95:104). Small SDs indicates that there was little change in the errors for successive attempts, which suggests that there was no change in tracking strategy.

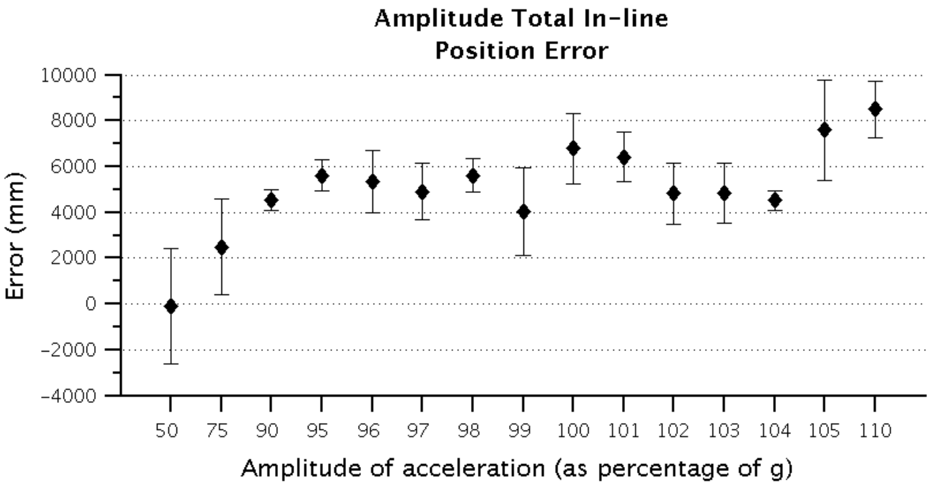


Figure 3-22. Gaze tracking (in the gaze only condition) total in-line position error means and SD at target acceleration amplitude.

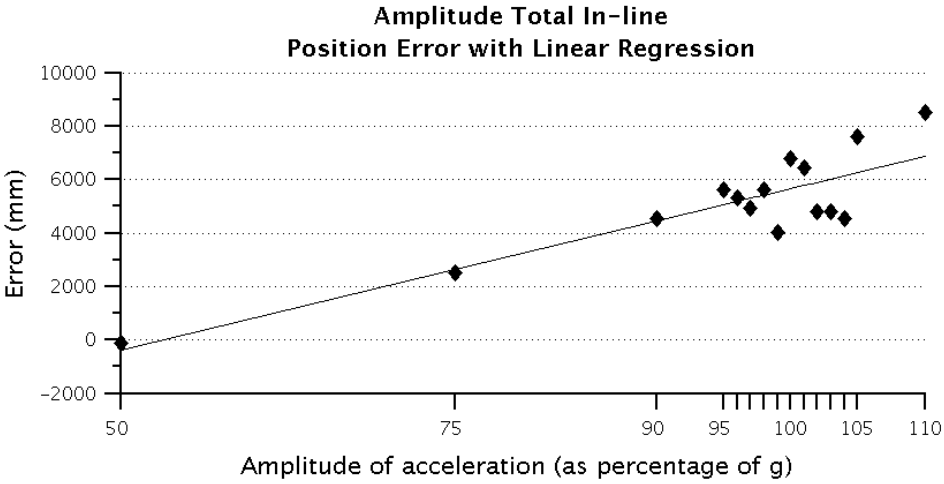


Figure 3-23. Gaze tracking (in the gaze only condition) total in-line position error means at target acceleration amplitude linear regression.

Total velocity and acceleration errors were not significantly affected by acceleration amplitude. All tracked velocities were lower than the target's and errors tended to increase as the target's acceleration increased though the trend was not strong and some SDs were large. All acceleration errors were positive (accelerations less than the target's) apart from when tracking a target accelerating at 50% of *g*. Acceleration errors tended to increase as the acceleration amplitude increased. These derivatives errors resemble the pattern of the position error in that tracking fell increasingly far behind as target acceleration increased.

3.3.4.4 Gaze only tracking: The effect of repetition (attempt no.) on the in-line component of tracking

Total position error was not significantly affected by attempt number ($F(2,16)=.496$, $p=.618$). Total velocity error ($F(2,16)=3.829$, $p=.044$) and total acceleration error ($F(2,16)=8.412$, $p=.003$) were significantly affected. Contrasts revealed that, for velocity, attempt 2 was significantly different from attempt 3 ($F(1,8)=8.788$, $p= .018$), and for acceleration attempt 1 was significantly different from attempt 2 ($F(1,8)=5.684$, $p=.044$).

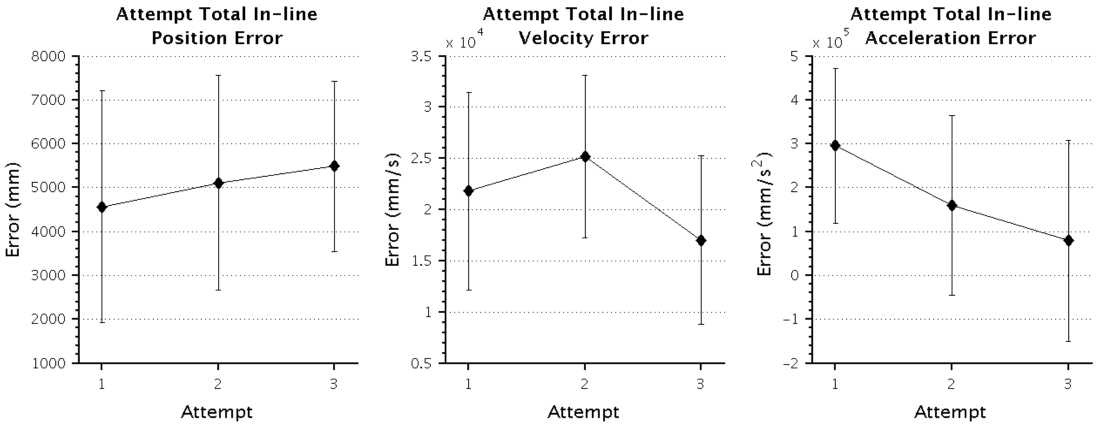


Figure 3-24. Gaze tracking (in the gaze only condition) total in-line position, velocity and acceleration error means and SD at tracking attempts.

There was no consistent pattern to the position error and derivatives. Large SD values suggest that tracking varied widely for a particular attempt (first, second or third) at different acceleration amplitudes.

3.3.4.5 Gaze only tracking: Amplitude-attempt interaction on the in-line component of tracking

For total position error there was no significant interaction between target acceleration and attempt number (uncorrected $F(24,224)=.528$, $p=.977$; GG $F(4.321,34.569)=.528$, $p=.729$; HF $F(10.028,80.221)=.528$, $p=.866$).

There is no consistent pattern to the attempt errors for all target accelerations (Figure 3-25). Errors over the range 90% to 104% of *g* are relatively consistent. However there appears to be an increase in error from the first to the second attempt when tracking a target accelerating at 105% and 110% of *g*; note though that there is no change at g104 so it may be that the error at g105 is anomalous. The change in error from the first to the third attempt in conditions with a slow moving target (50% and 75% of *g*) from leading to a small lag with repetition indicates that on first encounter, tracking was appropriate for a target that was expected to move faster than it did (i.e. an internal model predicting acceleration at *g* not at 50% or 75% of *g*). In contrast, for accelerations greater than *g*, error reduced with each attempt, in fact tracking lagged further behind, indicating that for accelerations in excess of 100% *g* there was a failure to adapt over three attempts.

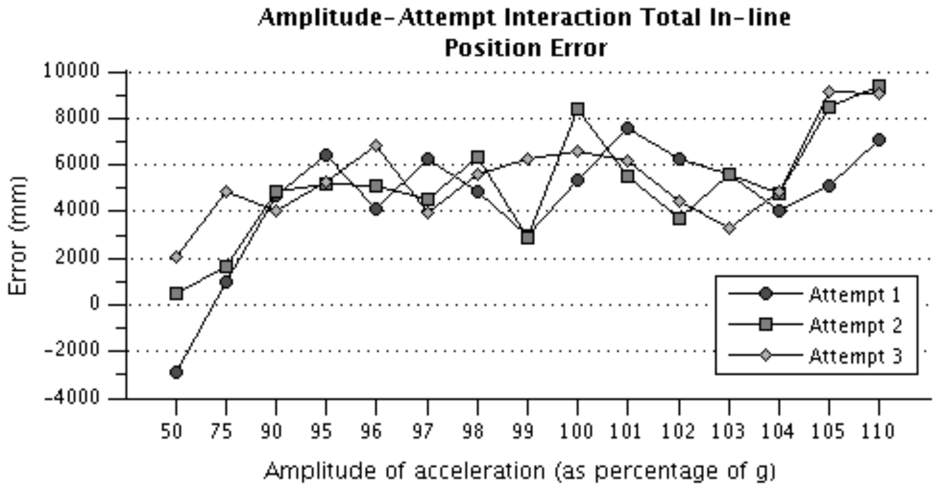


Figure 3-25. Gaze tracking (in the gaze only condition) total in-line position attempt error means at target acceleration amplitude.

3.3.5 Gaze tracking in the manual condition

3.3.5.1 Gaze tracking in the manual condition: Time series of tracked position, velocity and acceleration averaged across target acceleration amplitudes

The features of the attempt time series for gaze in the manual condition (Figure 3-26) are quite different from those for gaze in the gaze only condition:

- Tracking was below the target by ~75 mm at the start of the tracking period (almost twice the error as in the gaze only condition) meaning that gaze was at the very edge of the target circle at that time.
- There was little change in tracked position up to 200 ms when gaze then moved downwards but was always behind the target.
- At ~350 ms there is a first catch-up saccade that typically reduced the position error by approximately 80-100 mm. The height of the position error spike/peak before the saccade reduced with practice but there was no change in the distance gaze caught up with the target nor any difference in the timing of the saccade.
- Following this saccade the positive position error again increased (gaze falls further behind the target) up to ~550 ms when there is a second saccade that reduced position error by ~50 mm. Position error then increased once more.

A key feature of the position plots is that gaze never overtakes the target or re-enters the target's circumference once it has fallen behind.

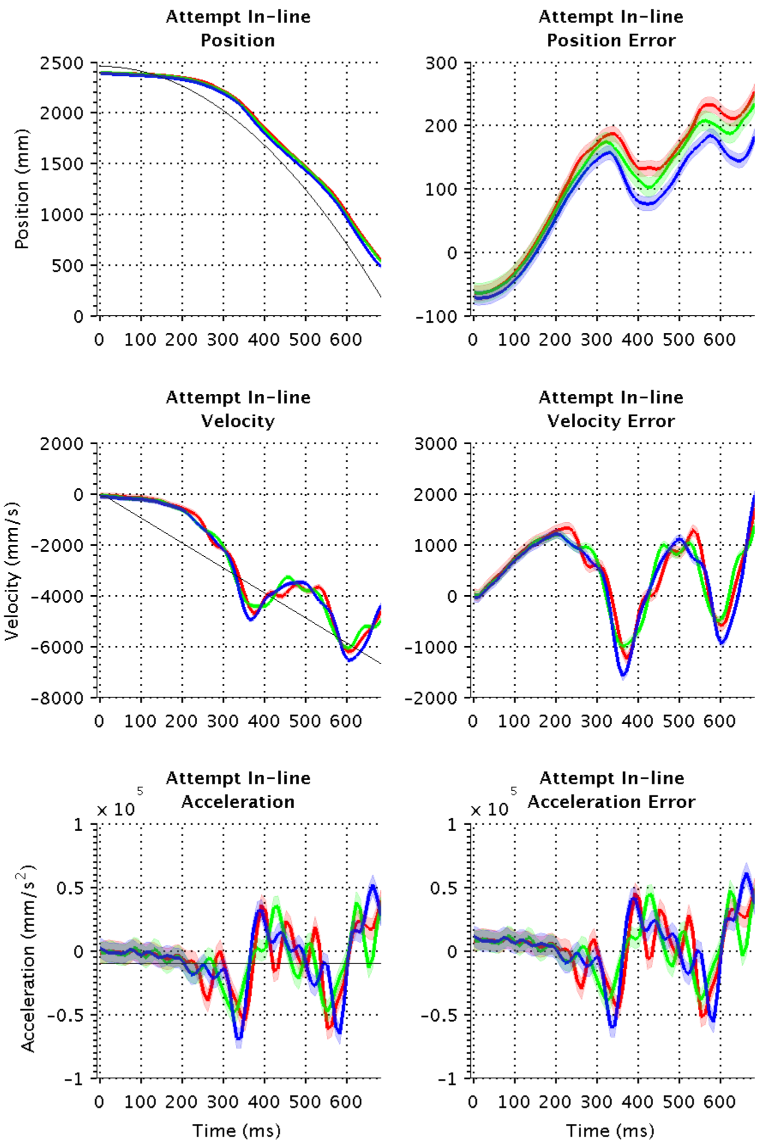


Figure 3-26. Time series of gaze tracked (in the manual condition) in-line position, velocity and acceleration for each attempt. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

3.3.5.2 Gaze tracking in the manual condition: Time series of tracked position error for each target acceleration amplitude

The position errors seen at different acceleration amplitudes for gaze in the manual condition (Figure 3-27) were quite different from those when gaze tracking in isolation. Tracking was ahead of the target (negative error) by ~100mm at the start of the tracking period (also found when manual tracking) but following this tracking fell increasingly behind the target (positive error) up to ~300-400ms where a catch-up saccade reduced position error or 'stalled' its increase. Following this event the tracked position generally fell increasingly further behind the target.

The tracking of targets accelerating at 50% or 110% of *g* are special cases. When tracking at g50 there was very little change in position error throughout the trial and between attempts. There is no first saccade at ~300 ms, presumably because smooth pursuit was adequate for staying on-target. When tracking at g110, the first sharp downwards deflection in gaze appears absent or smaller. This could be because any saccade was absent in some trials in these averages (across individuals) or was of very variable timing and so obscured in the average. Whichever was the case, the error does not substantially decrease but rather is fairly constant for a short before again increasing.

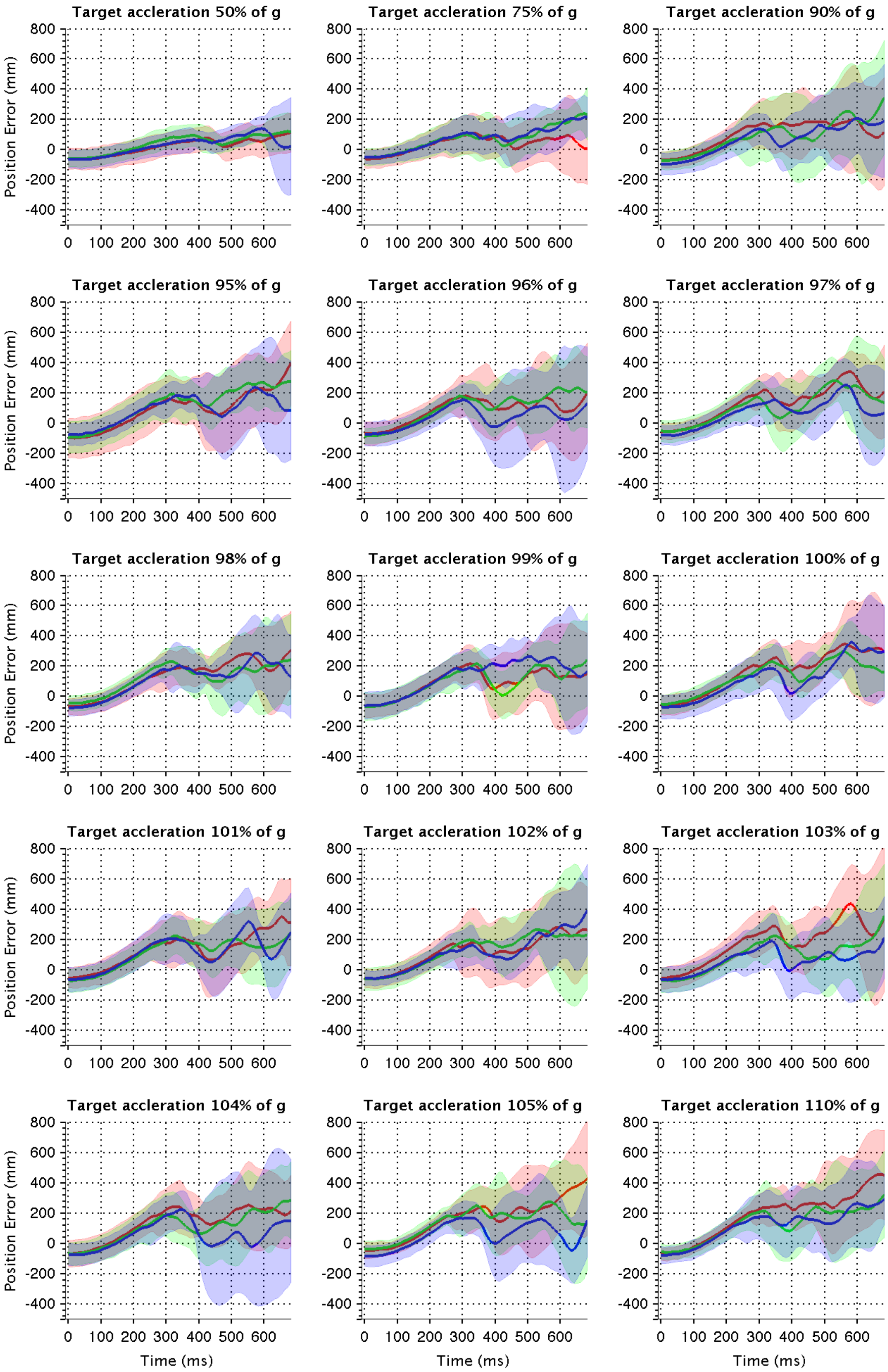


Figure 3-27. Time series of gaze tracked (in the manual condition) in-line position, velocity and acceleration for each acceleration amplitude condition. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

3.3.5.3 Gaze tracking in the manual condition: The effect of target acceleration amplitude on the in-line component of tracking

Total position error was significantly affected by target acceleration (uncorrected $F(14,112)=2.939$, $p=.001$; GG $F(4.184,33.473)=2.939$, $p=.033$; HF $F(9.345,74.757)=2.939$, $p=.004$). Contrasts revealed significant differences between g100 error and g50 error ($F(1,8)=38.182$, $p<.001$); g75 error ($F(1,8)=31.818$, $p<.001$); g95 error ($F(1,8)=9.347$, $p=.015$); g96 error ($F(1,8)=10.17$, $p=.013$); and g97 error ($F(1,8)=5.494$, $p=.047$).

The error pattern is similar to that seen in the gaze only condition though here the errors are approximately 2000 mm larger. Mean tracking error and SD tends to increase as the target acceleration increases. See Figure 3-28.

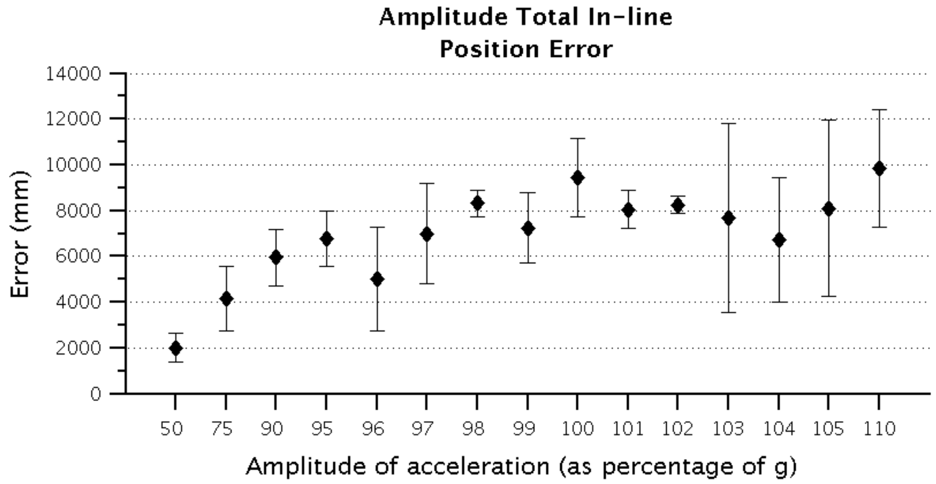


Figure 3-28. Gaze tracking (in the manual condition) total in-line position error means and SD at target acceleration amplitude.

Total velocity and acceleration were all positive and there was a tendency for the errors to increase as the target acceleration increased though no significant differences were found.

The overall pattern of gaze tracking in the manual condition is similar to that when gaze tracking in isolation but the mean errors for each amplitude condition were more positive (i.e. tracking was further behind, slower and accelerated less quickly than in the gaze only condition).

3.3.5.4 Gaze tracking in the manual condition: The effect of repetition (attempt no.) on the in-line component of tracking

Total position error was significantly affected by attempt number ($F(2,16)=5.002$,$p=.02$) but contrasts revealed no significant differences between attempts. Velocity and acceleration errors were not significantly affected by attempt number.

Though position and velocity errors decrease with practice, the acceleration errors increase (Figure 3-29).

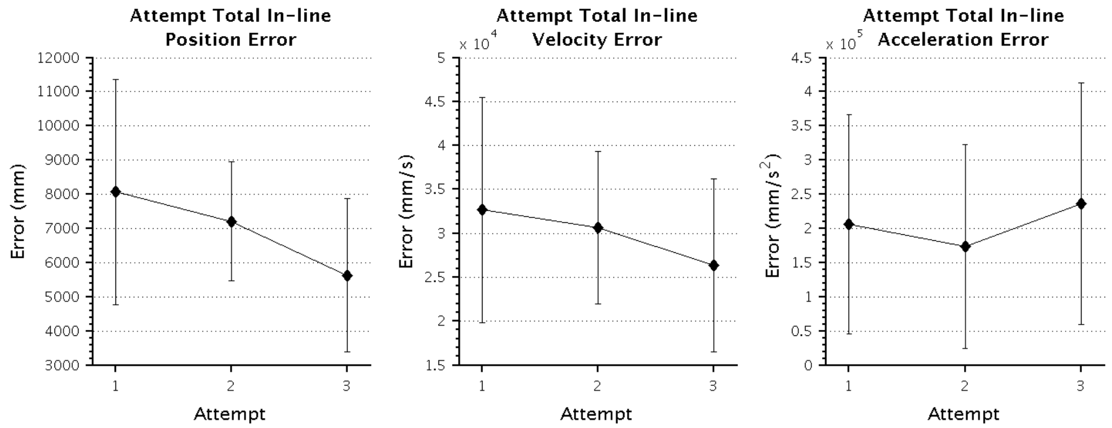


Figure 3-29. Gaze tracking (in the manual condition) total in-line position, velocity and acceleration error means and SD at tracking attempts.

3.3.5.5 Gaze tracking in the manual condition: Amplitude-attempt interaction on the in-line component of tracking

For total position error there was no significant interaction between target acceleration and attempt number (uncorrected $F(28,224)=1.307$, $p=.147$; GG $F(4.632,34.898)=1.307$, $p=.286$; HF $F(10.243,81.944)=1.307$, $p=.239$). However contrasts revealed a significant difference between attempt 1 and attempt 2 from g100 to g75 error ($F(1,8)=10.634$, $p=.012$). There is little clear and consistent change in attempt errors within acceleration amplitudes apart from at accelerations >102% of *g* where errors reduced with practice (Figure 3-30).

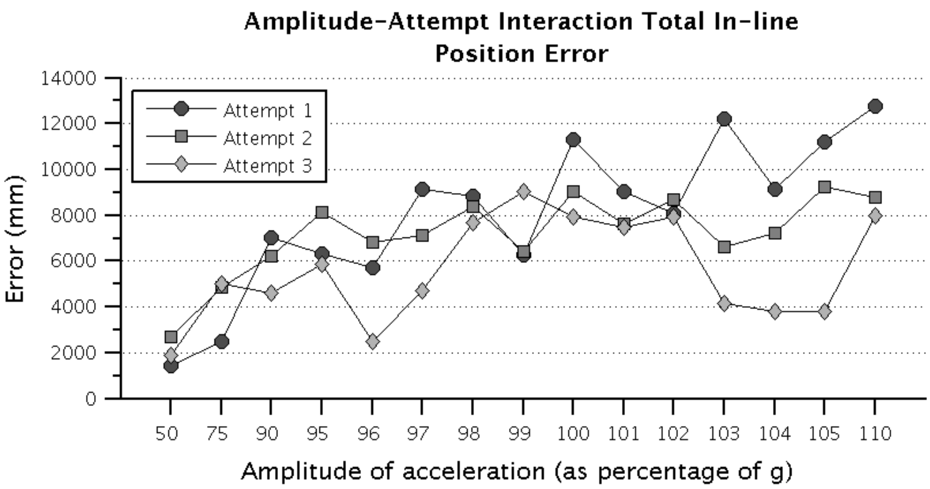


Figure 3-30. Gaze tracking (in the manual condition) total in-line position attempt error means at target acceleration amplitude.

The patterns found were similar to that in the gaze only condition.

3.3.6 Gaze tracking in the laser condition

3.3.6.1 Gaze tracking in the laser Condition: Time series of tracked position, velocity and acceleration averaged across target acceleration amplitudes

The attempt time series for gaze in the laser condition (Figure 3-31) is similar to that for gaze in the manual condition. The main features were:

- Tracking was below the target by ~40 mm at the start of the tracking period (similar to that in the gaze only condition).
- The tracked position fell behind the target ~150 ms after it began to move, and position error increased to a maximum at ~300 ms when an increase in gaze velocity reduced position error by ~25mm.
- Position error then increased again and only at the third tracking attempt was there a clear second saccade at ~500 ms that reduced position error again. Averaging over many different trials may have obscured any other saccades that occurred with inconsistent timing; small inflexions and wavelets on the traces suggest these were sometimes present.

Probably due to variation in timing of some catch-up saccades, the acceleration time series shows a quite complex pattern, although sharp downwards accelerations at ~250-350 and then ~525 ms can be distinguished. In the velocity time series, the tracked velocity clearly becomes closer to target velocity with practice. The reduction in velocity error to near zero at each attempt corresponds to the small reduction in position error at ~350 ms. These data show that gaze tracking in the laser condition was further behind the target than any other tracking.

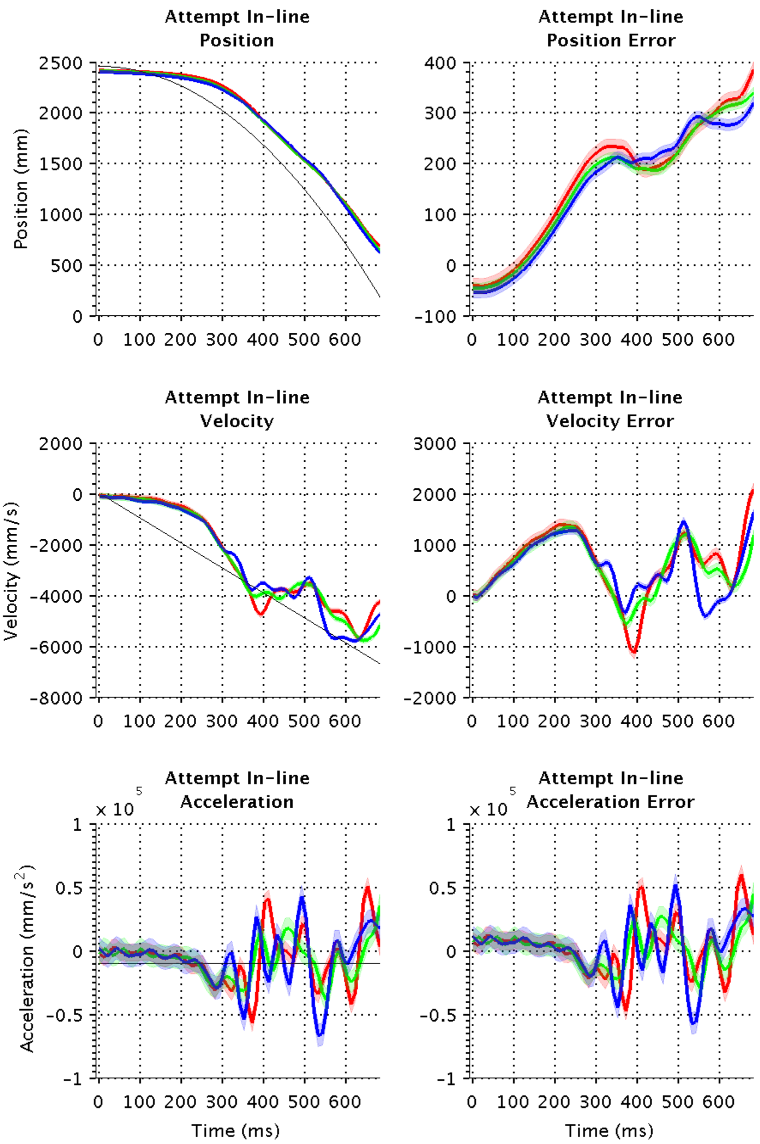


Figure 3-31. Time series of gaze tracked (in the laser condition) in-line position, velocity and acceleration for each attempt. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

3.3.6.2 Gaze tracking in the laser condition: Time series of tracked position error for each target acceleration amplitude

The individual time series of position error for gaze tracking in the laser condition for the different amplitude accelerations (Figure 3-32) show that the features identified in the pooled attempt time series (above) are not representative of tracking at every amplitude condition.

Only when tracking a target accelerating at ≥100% of *g* was there a clear reduction in position error over tracking attempts. When tracking at accelerations <100% of *g* there was either little or no change in error over the attempts or there appeared to be an increase in error (e.g. tracking at 96% of *g*). The tracking profiles for gaze in the laser condition appear to vary more between acceleration amplitudes than any other tracking condition.

Tracking error at the start of the trial was similar across all amplitudes at between 0 and -100 mm. Following this, error became positive and increased to between 300-400 ms where a catch-up saccade reduced position error or prevented its further increase. The timing of this saccade varied between amplitude conditions and tracking attempts but not in a way that has any obvious meaning. Such a catch-up saccade was present at ~300 ms in the other gaze conditions, and was more pronounced/clear than in this condition.

The turbulence of the position error over time probably indicates that saccade timings throughout the trials varied more than in the other gaze conditions, but error SD over time (shaded regions) is reasonably narrow suggesting that if this was the case, such variably timed eye movements nevertheless achieved tracked position errors that were not consequently large, and were approximately the same in each trial across different subjects.

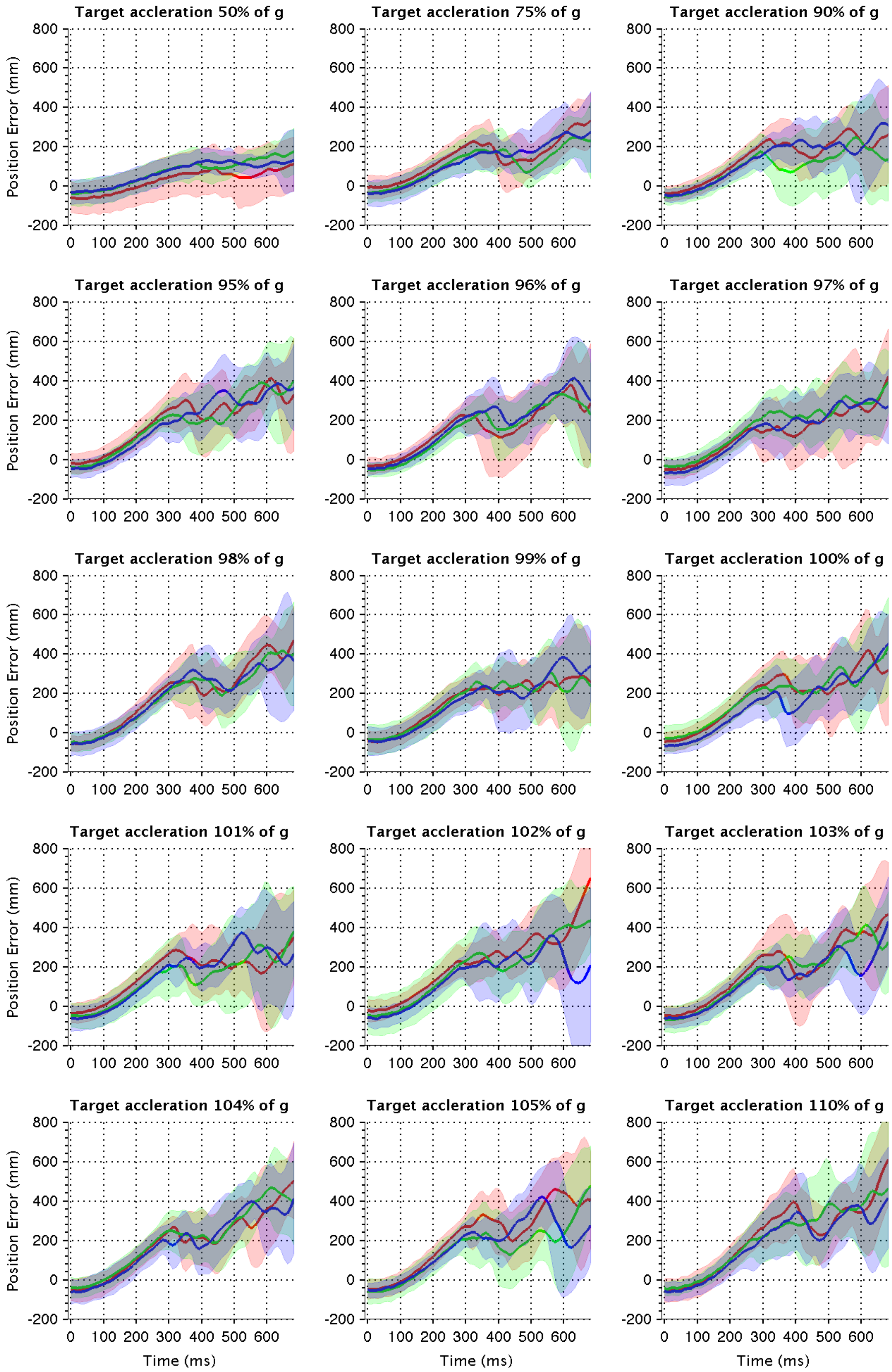


Figure 3-32. Time series of gaze tracked (in the laser condition) in-line position, velocity and acceleration for each acceleration amplitude condition. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD.

3.3.6.3 Gaze tracking in the laser condition: The effect of target acceleration amplitude on the in-line component of tracking

Total position error was significantly affected by target acceleration (uncorrected $F(14,112)=6.727$, $p<.001$; GG $F(5.857,46.857)=6.727$, $p<.001$; HF $F(14,112)=6.727$, $p<.001$). Contrasts revealed significant differences from g100 error to: g50 error ($F(1,8)=31.252$, $p=.001$); g75 error ($F(1,8)=8.675$, $p=.019$).

The total errors at each amplitude when gaze tracking in the laser condition were ~2000 mm greater than laser tracking errors and gaze tracking errors in the manual condition, and were ~4000 mm greater than gaze tracking errors in the gaze only condition. The pattern of error for different acceleration amplitudes is similar to all of those conditions. Tracking was least variable at g99. See Figure 3-33.

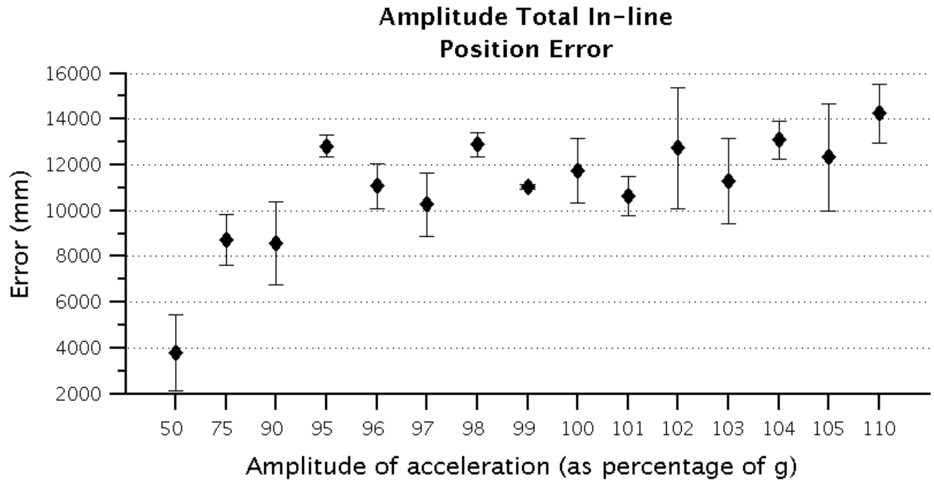


Figure 3-33. Gaze tracking (in the laser condition) total in-line position error means and SD at target acceleration amplitude.

Total velocity error was significantly affected by target acceleration (uncorrected $F(14,112)=4.825$, $p<.001$; GG $F(4.545,36.359)=4.825$, $p=.002$; HF $F(11.26,90.081)=4.825$, $p<.001$). Contrasts revealed significant differences from g100 error to: g50 error ($F(1,8)=11.411$, $p=.01$); g75 error ($F(1,8)=9.478$, $p=.015$); g90 error ($F(1,8)=6.418$, p=.035); g96 error ($F(1,8)=6.837$, $p=.031$); g99 error ($F(1,8)=7.492$, p=.026).

All errors were positive (tracking was slower than the target) and the error increased as target acceleration increased (Figure 3-34). These values were consistently greater than when laser tracking.

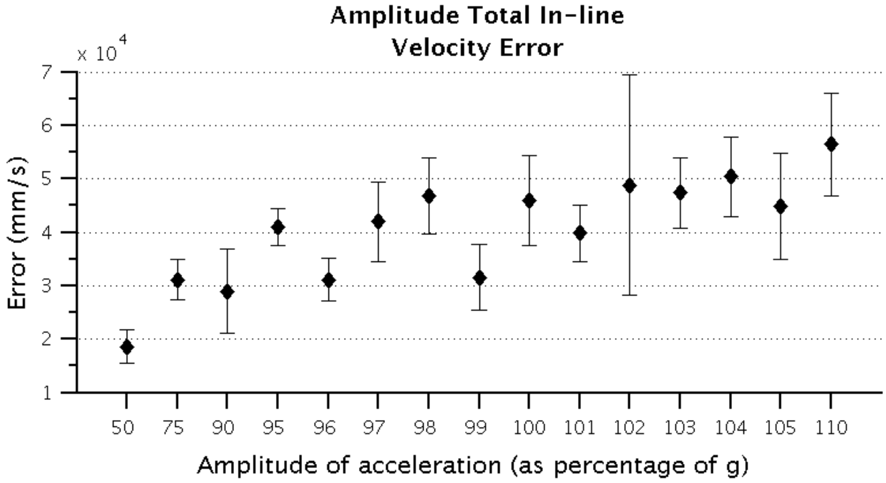


Figure 3-34. Gaze tracking (in the laser condition) total in-line velocity error means and SD at target acceleration amplitude.

Total acceleration error was not significantly affected by target acceleration. All errors were positive (tracking accelerating less than the target) apart from at g96 and g100.

3.3.6.4 Gaze tracking in the laser condition: The effect of repetition (attempt no.) on the in-line component of tracking

Total position error was not significantly affected by attempt number ($F(2,16)=2.883$, $p=.085$). Total velocity error was significantly affected by attempt number ($F(2,16)=4.782$, $p=.024$). Contrasts revealed for velocity that attempt 1 was significantly different from attempt 2 ($F(1,8)=5.879$, $p=.042$); total error was significantly greater for the first attempt.

For both total position and total velocity error, mean and SD values reduced for each attempt (Figure 3-35).

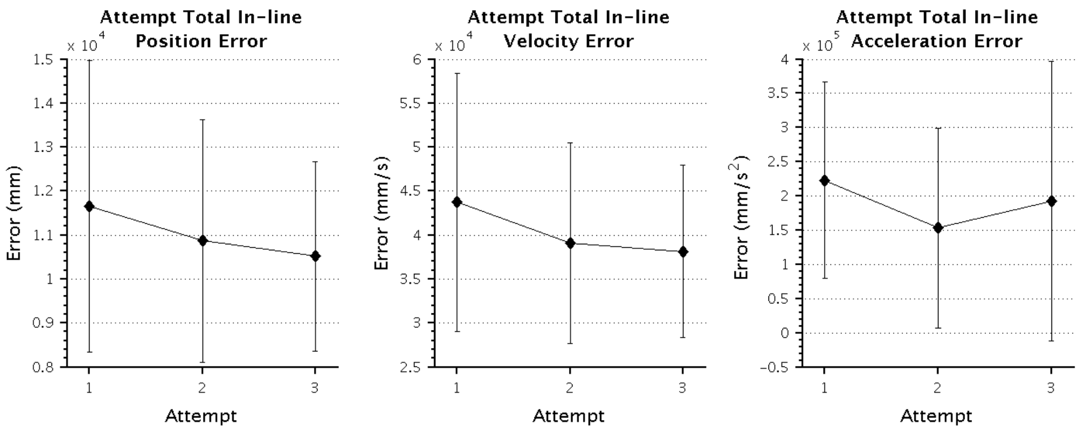


Figure 3-35. Gaze tracking (in the laser condition) total in-line position, velocity and acceleration error means and SD at tracking attempts.

3.3.6.5 Gaze tracking in the laser condition: Amplitude-attempt interaction on the in-line component of tracking

For total position error there was no significant interaction between target acceleration and attempt number (uncorrected $F(2,224)=1.381$, $p=.105$; GG $F(5.561,44.487)=1.381$, $p=.246$; HF $F(19.699,157.591)=1.381$, $p=.141$).

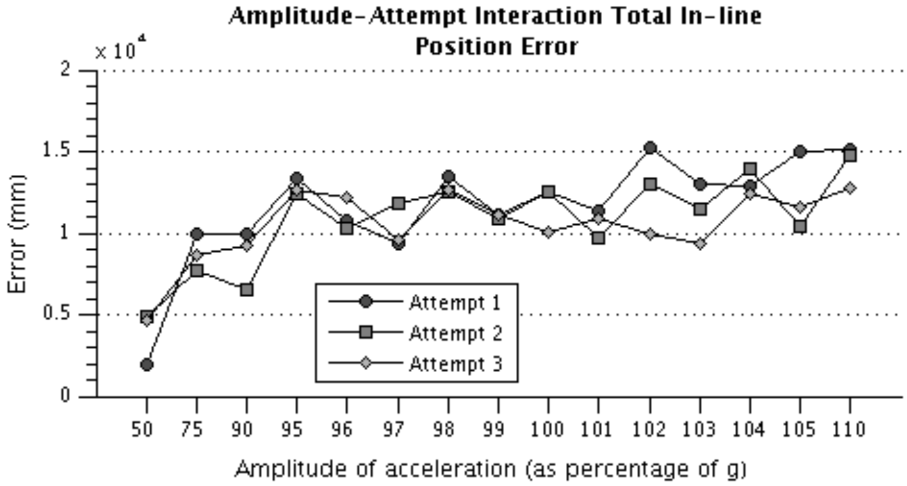


Figure 3-36. Gaze tracking (in the laser condition) total in-line position attempt error means at target acceleration amplitude.

For total velocity error there may have been a significant interaction between target acceleration and attempt number (uncorrected $F(2,224)=1.773$, $p=.013$; GG $F(4.545,36.359)=1.773$, $p=.124$; HF F(11.226,90.081)=1.773, $p=.015$). Contrasts revealed a significant difference between attempt 1 and attempt 2 from g100 to g90 error ($F(1,8)=8.467$, $p=.02$). See Figure 3-37.

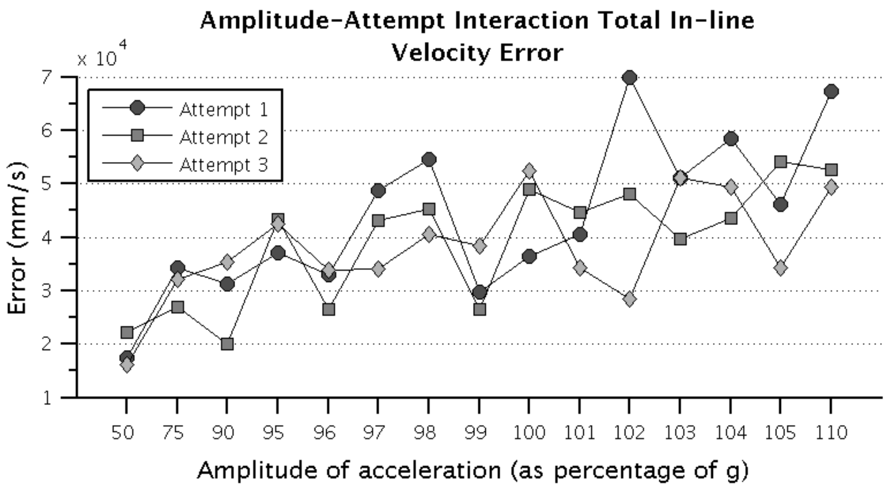


Figure 3-37. Gaze tracking (in the laser condition) total in-line velocity attempt error means at target acceleration amplitude.

3.4 Discussion

3.4.1 Main questions and findings

In the discussions that follow I present evidence suggesting that an internal model of gravity predicts that descending targets accelerate at, or at slightly less than, *g* (9.81 m/s^2). I now briefly outline several important features that will be examined in greater detail in following Discussion sections.

- The target's acceleration amplitude and the method of tracking had significant effects ($p<.001$) on tracking output so, each tracking method was examined separately. Gaze tracking in each condition (in isolation, with manual tracking and with laser tracking) differed highly significantly ($p<.001$) from each other. Consequently, within each method, I examined tracking differences across target trajectories, between attempts and tested for interactions.

- For all tracking methods, the total tracked errors were lowest for targets accelerating at 50% and 75% of *g*. If an internal model of gravity predicted target acceleration at *g* then tracking would be expected to be far ahead of the target at these low accelerations. But the low instantaneous velocities at these accelerations probably allow for corrections to planned movement from acquisition of visual information that contradicts predicted target movement.

- Manual tracking was ahead of, and faster than, the target for all target accelerations. These leads increased as the target's acceleration increased. There was a noticeable change in tracking error for target accelerations greater than 100% of *g* i.e. tracking output (and control) differed when targets accelerated *unnaturally quickly* that suggests the existence an internal model of gravity tuned to *g*.

- Laser tracking was behind and slower than the target for all target accelerations. All errors increased as target acceleration increased. When tracking accelerations ≥100% of *g*, first attempt errors continued to increase with target acceleration, but second and third attempt errors did not, suggesting that an internal model of gravity was predicting (at first exposure) target acceleration not greater than *g*.

- The pattern of saccades for gaze tracking in isolation and in the manual condition suggest an internal model predicted the position of targets based on an expected target acceleration close to g when tracking targets accelerating at between 90% and 100% of g.

- Gaze tracking in the laser condition followed the laser spot rather than the target itself.

3.4.2 Main effects on tracking output

In this experiment I used differences in tracking output under different target acceleration amplitudes to investigate the amplitude tuning of a possible internal model of gravity. Tracking output was measured under three main factor: target acceleration, tracking method and attempt number. A full-factor ANOVA found significant main effects for all factors and significant interactions for amplitude*attempt and mode*attempt (Results 3.3.1 and Figure 3-2). These main effects were broken down using one-way ANOVAs.

Target acceleration amplitude significantly affected tracking output (p<001). Tracking error at 50% of g was significantly lower (p<.05) than in any other acceleration condition apart from 75% of g, and tracking error at 75% of g was significantly lower (p<.05) than at 110% of g. This means that participants' tracking worsened as target acceleration increased.

Participants executed visually guided tracking of the target in three main ways: pointing a finger; pointing a laser; or gaze tracking. These are fundamentally different methods because – though mechanical, inertial and gravitational forces are not thought to affect tracking output (see Chapter 2 Discussion 2.4.4) – for manual and laser tracking, arm movements are mechanically slower than gaze transferring eye movements (which are not as susceptible to mechanical, inertial or gravitational forces). Further, the judgement of tracked position is different for all three main methods in that manual tracking requires the participant make a subjective judgement of their tracked position looking past the fingertip, whereas when laser tracking, the tracking output (laser spot) is clear and immediate; and when gaze tracking the target should simply be the focal point of attention, with judgement of tracking performance obtained from the retinal image of the target. The required tracking was identical for each tracking condition, though I found that laser, and all pooled gaze, tracking differed significantly (p<.001) from manual tracking but not from each other. Also, all gaze tracking methods (in isolation, with manual tracking and with laser tracking) differed significantly (p<.001) from each other.

The investigation of several tracking methods in the current experiment was therefore a great strength as it was in Chapter 2. As a result of the identified differences in tracking I analysed manual, laser and all gaze tracking methods separately using 2-way repeated-measures ANOVAs to identify differences between acceleration amplitudes, attempts, and interactions between these.

3.4.3 Gravitational and inertial influences

We do not believe gravitational and inertial influences to have affected tracking and load forces imposed by the laser are considered inconsequential (see Chapter 2 Discussion 2.4.4).

3.4.4 Sideways tracking

Trajectory plots revealed that the mean tracked position never deviated from the target's path more than the target's radius (75 mm) in every condition apart from the manual condition when tracking never deviated more than 125 mm from the target's path. There were no indications of sideways tracking movements relating to target accelerations in any conditions. These plots and information on sideways tracking (tracking perpendicular to direction of target travel) are not informative and are not included in this thesis.

3.4.5 Manual tracking

At the start of trials at all accelerations, manual tracking was 40-80 mm below target centre (Figure 3-5) – typically within the target radius of 75 mm. This offset is likely to result from maintaining both the target and the fingertip in sight to allow comparison of tracked position (a vector from the dominant eye to the finger tip that intercepts the screen plane) to target position (see Chapter 2 Discussion 2.4.2).

The errors when tracking targets accelerating at much less than *g* (50% or 75%) are probably so low and consistent because the trajectory was obvious and relatively easy to track due to the much lower instantaneous velocities involved than when tracking a target accelerating at *g*. Tracking ahead of the target, and increasing the distance tracked ahead as target acceleration increased, might be to deliberately enlarge tracking 'redundancy' i.e. participants by doing this certainly allowed more room for error as target movement evolved, making it less likely that sight of the target would be lost due to it being obscured by the arm/hand falling behind.

Total tracked position, velocity and acceleration showed tracking to be ahead (successfully) of/faster than the target at all acceleration amplitudes. Negative trends to velocity and acceleration amplitude data (Results 3.3.2.3) indicated that the tracking lead increased as the target's acceleration increased. The tracked error SD also increased with increasing target acceleration indicating that the attempt errors within each amplitude condition were becoming ever more different from one another. That is, the tracking output varied more widely between attempts as the target's acceleration increased. Time series plots (Figure 3-5) and interaction data (Results 3.3.2.5) indicate that this was the result of second and third attempt tracking moving increasingly further ahead of the first attempt tracking as the target's acceleration increased past >100% of *g*.

The pattern of errors in the plots of interaction total position error (attempt errors at each individual acceleration tested – Figure 3-8) was for first attempt errors to increase as target acceleration increases but for second and third attempt errors to not increase. This trend change with practice perhaps suggests that tracking at the first attempt might have been for an acceleration that was expected to be less than transpired (i.e. an expectation of *g* rather than anything greater), whereas in subsequent attempts tracking increased in overall speed as was typically the case (Figure 3-9). The individual time series of position error split by acceleration amplitude, though 'noisy', appear to confirm this.

At the start of trials tracking falls behind the target (for all acceleration amplitudes apart from g50) up to ~300 ms when tracking overtook the target (due to an acceleration pulse at ~300 ms – Figure 3-4) and increased the distance ahead for the remainder of the trial. As target acceleration increases, the distance fallen behind at the first attempt, and the distance tracked ahead at subsequent attempts typically increases with practice.

The change in error pattern for accelerations >100% of *g* indicates that participants' perception of their tracking output, at least at the first tracking attempt, was that it was inappropriate. That is, their prediction of target movement was poorer for targets that accelerated *unnaturally* quickly. Tracking errors for targets accelerating at 99% of *g* changed very little with practice, indicating that participants' perception was that their first track was good, and control was not required to change in subsequent attempts.

These tracking patterns suggest an internal model of gravity is predicting that the target will accelerate at *g*. However, target accelerations that were slightly less than *g* were well tracked, indicating that any model might be broadly tuned to cope with situations in everyday life where objects accelerate at slightly less than *g* due to viscous drag. However, because we never encounter free-falling acceleration greater than *g* in real life, the model's tuning parameters do not extend to any expectation of an acceleration of more than *g*.

3.4.6 Laser tracking

The main finding was that gaze tracking in the laser condition followed the laser spot rather than the target itself.

When using a laser, tracking was behind and slower (in velocity and acceleration terms) than the target for all target accelerations (Results 3.3.3.2 & 3.3.3.3). These errors increased linearly for total position and velocity error (Figure 3-14 and Figure 3-16). A linear relationship between error and target acceleration suggests that the control of tracked position within a trial is informed by current visual feedback of target position. Mean position error decreased from the first to the third attempt at each acceleration amplitude (apart from at 50% and 99% of *g*); see Figure 3-19. Also, there is an overall reduction in position error with practice (Figure 3-18). Change in error with practice indicates that control is not based solely on current visual feedback, but rather is modified based on historical visual feedback. In Chapter 2 I argued that laser tracking control was informed by a predictive model of gravity, and that the presence of immediate accurate visual feedback of tracked position (the laser spot) was prompting reliance on visual comparison of target position to tracked position. This caused tracking to trail the target as in the current experiment. Therefore, in the current experiment, a linear relationship between position error and target acceleration does not rule out a control contribution from an internal model of gravity predicting target position.

A key feature of the data suggesting that there was an internal model predicting target acceleration at *g* is that the mean position error decreased from the first to the second and third attempts for all target accelerations greater than 99% of *g* i.e. tracking on first encounter of an acceleration greater than *g* lagged because the model predicted *g* whereas second and third attempt tracking, informed by historical feedback, were with smaller lags. Though this also occurs at 90%, 97% and 98% of *g*, the decrease in error is not as consistent around those accelerations. Importantly there is virtually no change in error at 99% of *g*. This was also the case when manual tracking where it was apparent that control was predictive and informed likely to be by an internal model of gravity tuned to *g*. It is therefore likely that the pattern of errors when laser tracking is the result of control informed by an internal model of gravity, and by visual comparison of tracked position to target position, both online and historical.

Tracking errors at 50% and 75% of *g* were lower than all others. It seems likely that when targets accelerated at 90-99% of *g* there is a predictive model informing tracking control, but accelerations of 50% and 75% of *g* were too far from model tuning (at 99% or 100% of *g*) for the model to provide the best way of informing control. Rather, at these slow and unnatural accelerations it seems that mainly online visual feedback was used, and that this method coped well because of low target instantaneous velocities that meant feedback delays were not noticeably damaging to tracking output.

3.4.7 Gaze only tracking

The individual time series plots of tracking error for each target acceleration (Figure 3-21) show that at the start of tracking, gaze was close to the centre of the target; but the upwards drift in each plot indicates that tracking subsequently fell behind the target, by an amount rising to 200 mm in most cases. Total position errors (Figure 3-22) confirm this for all acceleration amplitudes (always positive error) and the total velocity and acceleration errors show tracking to be slower than, and accelerating less quickly than, the target (apart from acceleration error at g50). Though the pooled time series plot of attempt position error (Figure 3-20 – top right) show that gaze tracking trailed the target overall, that plot necessarily loses the detailed information on position error and SD that resulted in each individual acceleration condition (Figure 3-21) – the patterns of tracking error did vary depending on the target's acceleration amplitude.

Tracking was predominantly behind the centre of the target for all attempts in all acceleration conditions apart from the first attempt in the g50 condition (confirmed in the total position error interaction plot - Figure 3-25). This might seem to suggest a lack of any predictive component to tracking but this is probably not the case. For all acceleration conditions apart from g50 there is a catch-up saccade timed at ~300 ms that brings gaze close to the centre of the target (Figure 3-21). Following this saccade the position error SD typically increases and the mean error becomes less 'stable' though it does sometimes reduce to close to zero, with sharp downwards deflections, both indicating further catch-up saccades. When considering tracking control, the fact that the catch-up saccade at ~300 ms reduces error to near zero for all acceleration amplitude conditions is crucial. Tracking cannot rely on visual feedback of position error alone, because gaze would then saccade to behind the target due to the target's acceleration; and that distance behind would increase as target acceleration increased. Thus a flexible predictive method must have been employed.

The saccades typically begin at ~300 ms and end ~100 ms later (Figure 3-21). If I assume a saccade plan originating 50 ms prior to execution then any model has ~250 ms in which to gather information from the visual stimulus to predict target position at ~400 ms. There are three like1ly methods in which a model can predict future position:

- From the average velocity (AV) of the target from 0-250 ms.
- From the final velocity (FV) of the target at 250 ms.
- From the actual acceleration.

The estimated position of the target at 400 ms using the average velocity (0-250 ms) and final velocity (at 250 ms) is shown in Table 3-3. The average (AV) error is always 2.67 times the final velocity (FV) error, making final velocity considerably more accurate though this method leads to a 55.18 mm prediction error for the lowest acceleration (50% of *g*). The individual time series error plots show that mean gaze position typically saccaded to near zero error at 400 ms (Figure 3-21). This would not be the case if prediction were based on average or final velocity. It therefore seems likely that participants were employing a predictive model that used the target's acceleration.

There is, however, no reason why a model of each acceleration amplitude would exist; and it is furthermore unlikely that one could be established following a single brief exposure to movement. Indeed, this is confirmed by the observation that at the lowest accelerations tested (50%, 75% and 90% of *g*) the saccades *overestimated* the future target position at the first attempt, and this overestimation was progressively reduced or removed following practice (Figure 3-21). Consequently there appears to have been an expectation (and action based on that expectation) that the target would move faster than it did for those low acceleration amplitudes; and based on observed error at the first attempt, participants were able to modify or override such an expectation. This implies that participants were using a default acceleration amplitude of >90% of *g*.

Table 3-3. Position error at 400 ms if target position is prediction from average velocity (1-25 ms) or final velocity (at 25 ms) for each target acceleration amplitude.

	Acceleration	Avg. vel. (1-25 ms)	Final vel. (@25 ms)	Dispacement at 400 ms			Prediction Error	
g%	(mm/s^2)	(mm/s)	(mm/s)	Actual	From avg. vel.	From final vel.	From avg. vel.	From final vel.
50	4905	613.125	1226.25	49.05	245.25	337.21875	147.15	55.18125
75	7357.5	919.6875	1839.375	73.575	367.875	505.828125	220.725	82.771875
90	8829	1103.625	2207.25	88.29	441.45	606.99375	264.87	99.32625
95	9319.5	1164.9375	2329.875	93.195	465.975	640.715625	279.585	104.844375
96	9417.6	1177.2	2354.4	94.176	470.88	647.46	282.528	105.948
97	9515.7	1189.4625	2378.925	95.157	475.785	654.204375	285.471	107.051625
98	9613.8	1201.725	2403.45	96.138	480.69	660.94875	288.414	108.15525
99	9711.9	1213.9875	2427.975	97.119	485.595	667.693125	291.357	109.258875
100	9810	1226.25	2452.5	98.1	490.5	674.4375	294.3	110.3625
101	9908.1	1238.5125	2477.025	99.081	495.405	681.181875	297.243	111.466125
102	10006.2	1250.775	2501.55	100.062	500.31	687.92625	300.186	112.56975
103	10104.3	1263.0375	2526.075	101.043	505.215	694.670625	303.129	113.673375
104	10202.4	1275.3	2550.6	102.024	510.12	701.415	306.072	114.777
105	10300.5	1287.5625	2575.125	103.005	515.025	708.159375	309.015	115.880625
110	10791	1348.875	2697.75	107.91	539.55	741.88125	323.73	121.39875

The catch-up saccades indicate that gaze tracking control was guided by a second-order internal model of target motion. Unfortunately the noise inherent in the gaze data (such as from variable saccade timings) make it difficult to identify a particular amplitude ‘optimum’ for such a model though our evidence is that ‘tuning’ was to a value between 90 and 100% of *g*.

3.4.8 Gaze tracking in the manual condition

The pattern of these gaze errors is generally similar to those in the gaze only condition but all errors when gaze tracking in the manual condition were larger.

At the first sample in the gaze only condition, gaze was ~30 mm below the start location of the target (Figure 3-21) but gaze tracking in the manual condition at the same sample was ~75 mm below the target (Figure 3-27) – at the edge of the target (75 mm radius). At the start of the trial gaze seems therefore to have been focussed on or past the fingertip, rather than on the target. This would lead to negative position error because the position of manual tracking was below the target at the 1st sample by approximately the same amount as gaze tracking in this condition with concomitant manual tracking.

Tracking was behind the target and slower than it in all measures. The total distance behind the target (Figure 3-28) increased as the target’s acceleration increased and the velocity and acceleration errors also tended to increase in this manner. Plots of total position error for each attempt at each acceleration tested (Figure 3-30) confirm increased error with increasing target acceleration. Those plots also show that the reductions in attempt position error (significant for total position error; Figure 3-29) were mainly due to the reduction in error at accelerations ≥100% of *g* for total position error. The individual time series position error plots (Figure 3-27) show that the position error did decrease following practice but only when tracking an acceleration of

97%, 100% and, most clearly, at ≥103% of *g* (this interaction effect between acceleration amplitude and repetition can also be seen in Figure 3-30). At other acceleration amplitudes there appears to be no change (e.g. 98% of *g*) or a small increase in error (e.g. 75% of *g*) with practice. Such changes in error with practice were not found when gaze tracking in isolation, indicating some interference from manual tracking. However, manual tracking does not appear to have disrupted participants' ability to saccade to target position following a period of increasing lag up to ~300 ms (Figure 3-27) for all acceleration amplitudes apart from 110% of *g*. This, as discussed in relation to gaze tracking in isolation (Results 3.4.7), indicates that participants were able to predict the upcoming position of the target.

Thus, gaze tracking with concomitant manual tracking appears to be controlled by an internal model predicting target motion as appeared to be the case for manual tracking and gaze tracking in isolation. Just as for gaze tracking in isolation, it is not possible to identify precise amplitude tuning of the model but catch-up saccades for first attempt tracking are typically less successful for unnatural accelerations greater than *g*.

3.4.9 Gaze tracking in the laser condition

Gaze tracking in the laser condition was further behind and slower than gaze tracking in isolation and gaze tracking in the manual condition.

Tracking was behind and slower than the target for all measures apart from when tracking accelerations of 96% and 100% of *g* in the total acceleration error (Results 3.3.6.3). Total position and velocity error increased as the target's acceleration increased (Figure 3-33 & Figure 3-34). Plots of the position and velocity attempt error showed that error reduced with practice (Figure 3-35). However, a reduction in error with practice was not consistent across all acceleration amplitudes as shown by plots of position and velocity attempt error for each acceleration tested (Figure 3-36 & Figure 3-37). The time series plots of position error at each individual acceleration (Figure 3-32) showed that a first saccade at ~300-400 ms is common to each acceleration amplitude. This saccade did not reduce error to near zero, apart from when tracking a target accelerating at 50% of *g*, and the effectiveness of the saccade (i.e. the reduction in error) declined as the target acceleration increased.

Increasing error as target acceleration increases, the lack of clear improvement with practice, and that saccades do not return position error to near zero might suggest that there is no internal model of target acceleration guiding control of gaze in the laser tracking condition. However, in the previously described experiment (Chapter 2 -

investigating directional aspects of an internal model of gravity) I found that gaze in the laser condition followed the laser spot rather than the target itself (Chapter 2 Discussion 2.4.9) so it is likely that the same occurred in the current experiment.

Indeed, in the current experiment I found that laser tracking was behind the target and that gaze during laser tracking (Gaze-Laser) was behind even laser tracking. Gaze tracking of the laser spot might occur because in the Gaze-Laser condition the participant is presented with instantaneous accurate feedback of tracked laser position, whereas in the Gaze-Only and Gaze-Manual conditions only the target is present on the screen. I must assume that participants' gaze tracking was to the best of their ability in the Gaze-Only and Gaze-Manual conditions, so tracking errors in these two conditions can be seen as a 'baseline' against which I can compare Gaze-Laser tracking.

Gaze-Laser tracking minus laser tracking was behind the laser spot by a similar amount as Gaze-Only tracking was behind the target, but typically less behind than Gaze-Manual tracking was behind the target (Figure 3-38). The differences between Gaze-Laser tracking minus laser tracking and Gaze-Only *appear* slightly greater than found in Chapter 2, but they actually differ by similar amounts (typically ~2500 mm at each amplitude/direction) in both experiments. For the current experiment, the data indicate that Gaze-Laser tracking pursued the laser spot in a way similar as Gaze-Only tracking was pursuing the target. The presence of the laser spot appears to have prompted reliance on laser feedback for Gaze-Laser tracking as it did for laser tracking itself.

Figure 3-38. Total in-line errors when tracking differently accelerating targets. Traces show manual tracking error (M), laser tracking error (L) and gaze tracking error under different conditions (GO = gaze only, GM =

manual condition, GL = laser condition). In addition, the dotted red line shows gaze relative to pointing intercept in the laser condition (GL-L).

Because gaze in the laser condition followed the laser spot, it is difficult to use the pattern of errors in the Gaze-Laser condition to support an internal model of gravity. However, the similarity of Gaze-Laser errors to Gaze-Only errors after 'controlling' for the effect of laser tracking, suggests the gaze tracking was controlled in the same way in both conditions. This control in Gaze-Only tracking appeared to be guided by an internal model of gravity so it is likely that Gaze-Laser tracking would be similarly guided.

3.4.10 Believable stimuli

In Chapter 2 I concluded participants considered stimuli to be realistic (Chapter 2 Discussion 2.4.10). Stimuli in this experiment were generated in the same way and participants again gave verbal report of the realistic nature of the target. It is interesting to note that several participants verbally reported that target movement was eerie and unnatural following tracking at 50% and 110% of *g*.

3.4.11 Duration of target visibility

As in Chapter 2, the size of the screen's rendering area limited the target's travel time. I restricted the analysis period to the maximum time that the fastest accelerating target (110% of *g*) was visible – 690 ms (see Method 3.2.6). This is only 40 ms less than in Chapter 2 and should still be sufficient time to overcome visuomotor delays of 150-200 ms (Zago et al., 2008)

The time series plots split by acceleration amplitude show modifications of tracking behaviour with practice that indicates the duration of target visibility was sufficient to collect information on tracked position relative to target position. Furthermore, catch-up saccades when gaze tracking in isolation and in the manual condition indicate sufficient time to judge target motion. Thus the presentation time was satisfactory to both observe tracking behaviour and infer underlying control mechanisms.

3.4.12 Control by an internal model

In Chapter 2 I found that tracking of realistic targets 'falling' in different directions at *g* appeared to be controlled using the output of an internal model of gravity and I found no evidence of control guided by 'direct perception' (direct extraction of information from the visual scene rather than derivation from experience – see Chapter 1 section 1.2.4).

Much like the experiment described in Chapter 2, in the current experiment I am able to differentiate between these two theories because the target's only variable property is its acceleration value. If 'direct perception' were employed then one would expect near identical tracking errors for each acceleration amplitude because the visual scene contains all information required to predict target motion. If an internal model were used then I would expect tracking error differences for each acceleration amplitude. The evidence I obtained for every tracking condition (manual and laser tracking, gaze tracking in these conditions and gaze tracking in isolation) is that tracking errors varied systematically depending on target acceleration amplitude. Specifically I have found evidence that:

- Tracking errors increased as target acceleration increased but errors typically decreased with practice.
- Manual tracking errors vary the least when tracking a target accelerating at close to (99% of) *g* within the 'naturally believable' range of 90% to 110% of *g*.
- Saccades when gaze tracking in isolation and in the manual condition typically 'over-shoot' (over-estimate change in target position) the target for very slow accelerations (e.g. 50% and 75% of *g*), typically reduce tracking error to near zero for 'natural/realistic' target accelerations (e.g. 90-100% of *g*) and typically 'undershoot' (under-estimate change in target position) for very fast accelerations (e.g. 105% and 110% of *g*).
- SD of tracking error is typically least when the target accelerates at 99% or 100% of *g*.

These differences cannot be explained in 'direct perception' terms and so argue in favour of visuomotor control achieved through an internal model of acceleration due to gravity (*g*).

3.4.13 Is there amplitude tuning of the internal model of gravity?

To assess internal modelling of gravity many studies compare participants' interception performance of naturally behaving stimuli (i.e. descending at *g*) with that of unnaturally behaving stimuli (e.g. ascents at *g* or constant velocity descents) e.g. constant velocity 'descending' targets in a 0*g* environment (McIntyre et al., 2001); constant velocity and 1*g* descending/ascending targets (Le Séac'h et al., 2010; Senot et al., 2012, 2005); and 0*g* or 1*g* descending targets (Zago et al., 2004, 2005). In these studies, even with visual information to the contrary, participants predict that targets will move naturally. However, the velocity/acceleration of such stimuli were gross manipulations of natural aspects of free-falling objects and so the acceleration amplitude aspects of an internal model of gravity have never been fully established. In the current study I presented targets accelerating at *g* and at small and large percentages of *g* to investigate the acceleration aspect of the directionally tuned internal model of gravity that I established in Chapter 2.

The aim of the current study (to investigate amplitude aspects of an internal model of gravity) was more difficult to fulfil than that of the previous experiment (to investigate directional aspects of an internal model of gravity) because the manipulations of target kinematics are more subtle – percentage of *g* acceleration rather than trajectory direction. Consequently the answers are less precise, but still point to amplitude tuning appropriate to the real world – between slightly less than *g* and *g*.

3.4.14 The importance of multiple tracking methods

The use of several different tracking methods is a great strength of this study for the same reasons as it was in the experiment described in Chapter 2 (Discussion 2.4.14). Despite the differences in output from each tracking method condition, the interpretation of results from each has led us to the conclusion that there is an internal model of gravity that is amplitude tuned to near *g*. As in Chapter 2, had I only tested a single tracking method I might have reached a different conclusion. Two such examples are:

- If interpreting only laser tracking then I might have suggested that tracking is based mainly or only on feedback of tracking position given by the laser spot, with the spot following the target (Discussion3.4.6) and the eyes following the spot (Discussion 3.4.9); whereas when manual tracking (without such augmented/accurate visual feedback) control is more clearly by application of an internal model of gravity (Discussion 3.4.5).
- Without the condition of manual tracking by finger pointing, I might have reached weaker conclusions on the model's amplitude tuning which resulted in the least change between attempts at 99% of *g* in this condition.

3.4.15 Conclusions

- The CNS appears to construct and maintain an internal model of gravity that is tuned towards near to, and just below, *g*.
- This model predicts that the movement of observed 'freely-moving' stimuli will be in a natural real-world manner i.e. accelerating at *g* or slightly less than *g*.
- Practice at persistently unnatural accelerations can modify the model as would be expected from a model that is required to predict the motion of a variety of freely moving targets that will have different acceleration profiles caused by variable environmental effects and different target densities and shapes.

3.4.16 Further work

A. Explore acceleration tuning for different directions. Interception performance for targets with natural kinematics (i.e. descent at *g*) is typically compared with that for targets with unnatural kinematics (e.g. ascents at *g* or constant velocity ascents/descent) when investigating internal modelling of gravity (Le Séac'h et al., 2010; Senot et al., 2012, 2005; Zago et al., 2004, 2005). In an effort to more narrowly define the acceleration amplitude tuning of such a model I tested only descents at percentages of *g* but it would be interesting to combine aspects of the current study with aspects of the experiment described in Chapter 2 to investigate tracking at trajectories that I have not yet tested. Targets could have natural kinematics (e.g. decelerating ascending targets or accelerating descending targets) or unnatural kinematics (e.g. decelerating descending targets, accelerating ascending targets, or constant velocity ascending/descending targets). Confirmation of directional and amplitude tuning of the internal model of gravity should arise from comparison of tracking errors for naturally versus unnaturally moving targets.

B. Transient target disappearance. In Further Work of the previous experiment I proposed a study using a very large stimulus presentation area so that targets could transiently disappear during tracking (see Chapter 2 Discussion 2.4.16). I propose an addition to such an experiment where acceleration of targets could be manipulated in a similar way to that described in the current experiment. In Chapter 2 Discussion 2.4.16 I stated 'tracking that is accurately maintained during transient disappearance or tracking that reaches the reappearance location simultaneously with the target would indicate persistent output of an internal model of gravity'. In the proposed experiment this would also be true for tracking targets accelerating downwards at near *g* but tracking unnaturally quickly or slowly accelerating target would present a pattern of errors congruent with the expectation of natural motion if an internal model of gravity is predicting target motion.

C. Conscious discrimination of 'natural' accelerations'. In Chapter 4 I describe an experiment that investigates the conscious discrimination of the direction (leftwards, on the vertical or rightwards) of a target accelerating at *g* in a straight line. That experiment used the same stimuli and presentation protocol as described Chapter 2. The results described in Chapter 4 correlate strongly with those in Chapter 2. It would therefore be interesting to conduct a similar experiment using the stimuli of the current experiment to assess participants' ability to discriminate whether a target that descends vertically in a straight line is accelerating slower than *g*, at *g* or faster than *g*.

3.5 References

Baurès, R., Benguigui, N., Amorim, M.-A., & Siegler, I. A. (2007). Intercepting free falling objects: better use Occam's razor than internalize Newton's law. *Vision Research*, *47*(23), 2982–91.

Field, A. (2009). *Discovering Statistics Using SPSS* (Third.). London: SAGE Publications.

Lacquaniti, F., & Maioli, C. (1989a). Adaptation to suppression of visual information during catching. *Journal of Neuroscience*, *9*(1), 149–59.

Lacquaniti, F., & Maioli, C. (1989b). The Role of Preparation in Tuning Anticipatory Responses During Catching -. *Journal of Neuroscience*, *9*(January), 134–148.

Le Séac'h, A. B., Senot, P., & McIntyre, J. (2010). Egocentric and allocentric reference frames for catching a falling object. *Experimental Brain Research*, *201*(4), 653–62.

McIntyre, J., Zago, M., Berthoz, A., & Lacquaniti, F. (2001). Does the brain model Newton's laws? *Nature Neuroscience*, *4*(7), 693–4.

Senot, P., Zago, M., Lacquaniti, F., & McIntyre, J. (2005). Anticipating the effects of gravity when intercepting moving objects: differentiating up and down based on nonvisual cues. *Journal of Neurophysiology*, *94*(6), 4471–80.

Senot, P., Zago, M., Le Séac'h, A., Zaoui, M., Berthoz, A., Lacquaniti, F., & McIntyre, J. (2012). When up is down in 0g: how gravity sensing affects the timing of interceptive actions. *Journal of Neuroscience*, *32*(6), 1969–73.

Vishton, P. M., Reardon, K. M., & Stevens, J. a. (2010). Timing of anticipatory muscle tensing control: responses before and after expected impact. *Experimental Brain Research*, *202*(3), 661–7.

Zago, M., Bosco, G., Maffei, V., Iosa, M., Ivanenko, Y. P., & Lacquaniti, F. (2004). Internal models of target motion: expected dynamics overrides measured kinematics in timing manual interceptions. *Journal of Neurophysiology*, *91*(4), 1620–34.

Zago, M., Bosco, G., Maffei, V., Iosa, M., Ivanenko, Y. P., & Lacquaniti, F. (2005). Fast Adaptation of the Internal Model of Gravity for Manual Interceptions: Evidence for Event-Dependent Learning. *Journal of Neurophysiology* (pp. 1055–68).

Zago, M., McIntyre, J., Senot, P., & Lacquaniti, F. (2008). Internal models and prediction of visual gravitational motion. *Vision Research*, *48*(14), 1532–8.

CHAPTER 4
CONSCIOUS DISCRIMINATION OF TARGET PATH ANGLE AND THE EFFECT OF PHYSICS EXPERTISE

So far, I have investigated the existence of an internal model of gravity using participants' success/error at tracking targets that move in natural or unnatural ways. To be successful in those tasks, predictive control of movement by the participant was necessary. This study allowed participants time to consider their reaction to the stimuli used in Chapter 2 and thus might reveal something new about the perception of the direction of movement of naturally accelerating targets. I investigated the ability of participants to discriminate whether a target accelerating at *g* was moving vertically, or to the left or right of the vertical. Previous studies have shown that in similar discrimination tasks a participant's report was influenced by an expectation that gravity would affect the trajectory. Consequently I expected that small deviations from the vertical (trajectories of only 1° left/right of vertical) were more likely to be reported as on the vertical than answered correctly. This was indeed the case, suggesting that participants had an expectation that objects would fall vertically even when observed dynamics contradicted this. Data were analysed by grouping participants as physics experts or novices, and as an ungrouped set. Physics expertise yielded no difference in performance. This suggests that performance, based on an internal model of gravity, is determined by experience of seeing things fall in the real world gravity, rather than intellectual understanding of gravity.

4.1 Introduction

Observers of a virtual target that moves in a straight line, and then disappears, report the target's final position to be ahead of its true final position in the direction of target motion regardless of target direction (Finke et al., 1986; Finke & Freyd, 1985; Hubbard & Bharucha, 1988; Hubbard, 1990; Nagai et al., 2002) and the reported distance ahead increases as the target velocity increases (Finke et al., 1986; Hubbard & Bharucha, 1988; Hubbard, 1990) – 'representational momentum'. The implication from these findings is that a prediction is made of future target position based on the information gleaned from observing its movement. This is in line with the ideas previously examined regarding on-line prediction of movement based on observed stimuli i.e. the faster that something moves, the further from the observed location one will predict its future position will be from that location (see Chapter 3). This effect also appears to be influenced by a gravitational pull since ascending targets are reported as being less far ahead than descending targets, and horizontally moving targets are typically reported as having moved downwards (Hubbard & Bharucha, 1988; Nagai et al., 2002) – 'representational gravity'. Therefore, there appears to be some internalisation of real-world effects on virtual targets in terms of their predicted motion.

We examined this effect using the stimuli described in Chapter 2 (targets accelerating at *g* and moving in a straight line vertically, or at different angular deviations off the vertical). The studies cited above were conducted on a computer monitor, whereas our target was a life-sized image of a 15 cm diameter ball, with an acceleration of true *g* (9.81 m/s^2) and a much larger travel distance (with some part of the target still visible, the centre of the target could travel 2.475 m – see Chapter 2 Methods 2.2.5). I asked participants to report the direction of target movement (on the vertical, to the left of vertical or to the right of vertical) for each target trajectory.

Given that previous studies have shown an expectation of gravitational effect on movement, I predicted that at the smallest angular deviation from the vertical (1° left/right) the target motion would be assumed to be vertically down; and that other trajectories, with more obvious angular deviations, might be perceived correctly.

4.2 Methods

4.2.1 Participants

Fifteen subjects participated (8 male, 7 female, mean age ± SD: 29.8±4 years) in this experiment. Nine subjects were classed as 'experts' (5 male, 4 female, mean age ± SD: 28.7±4.2 years) having studied physics beyond UK GCSE level and six, who had not, were classed as 'novices' (3 male, 3 female, mean age ± SD: 32.3±2.5). All participants reported normal or corrected to normal vision (using contact lenses), no neurological or sensorimotor disorders, and gave informed consent prior to participation. Experimental procedures were approved by the local ethics committee.

4.2.2 Experimental setup and stimuli

Stimuli and the apparatus were the same as described in Chapter 2, though gaze and marker tracking apparatus and their associated paraphernalia were not employed.

4.2.3 Task

The same stimuli used in Chapter 2 were used in this experiment. Following each triplet (3 identical target motions) participants declared on a questionnaire whether they thought that the target trajectory was on the vertical, or moved to the left of the vertical or to the right of the vertical.

4.3 Results

4.3.1 Un-grouped performance

The performance of participants is shown in Figure 4-1. The percentage of correct answers is shown (wide grey bars) and, where answers were incorrect, the percentage of responses for the given direction is shown (narrow red/green/yellow bars).

Performance when judging a trajectory >1º from the vertical was excellent. There was a bias for thinking trajectories descended vertically when they were, in fact, moving at 1º off the vertical; >50% of responses were incorrect at these angles and were marked as vertically downwards (Figure 4-2). Other target directions occasionally marked as vertical were 2º left (4.4% [2 occurrences, 1 occurrence = ~2.2%]) and 2º right (2.2%). A small percentage of vertically downwards trajectories were believed to fall 1º leftwards (11.1%) and 1º rightwards (13.3%) (Figure 4-1). Interestingly, 20% of ascending trajectories were believed to be moving leftwards but none rightwards. A few (6.7%) of trajectories moving 4º rightwards were marked as moving to the left and the same percentage moving 4º leftwards were marked as moving to the right.

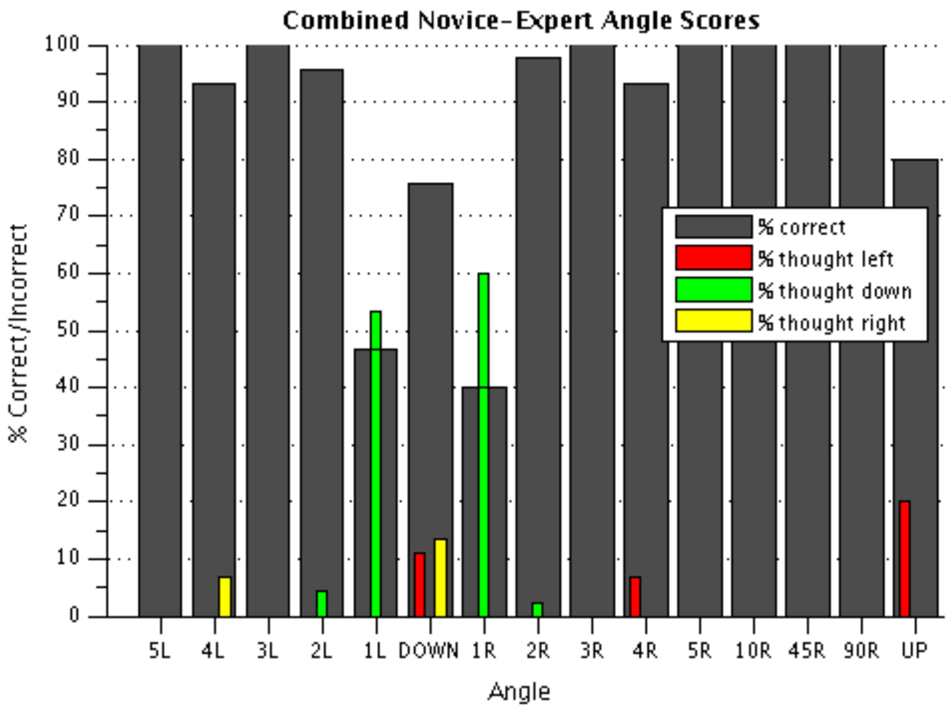


Figure 4-1. Percentage of correct answers for target directions and, where answers are incorrect, the percentage of responses given for other directions (left/down/right) is shown.

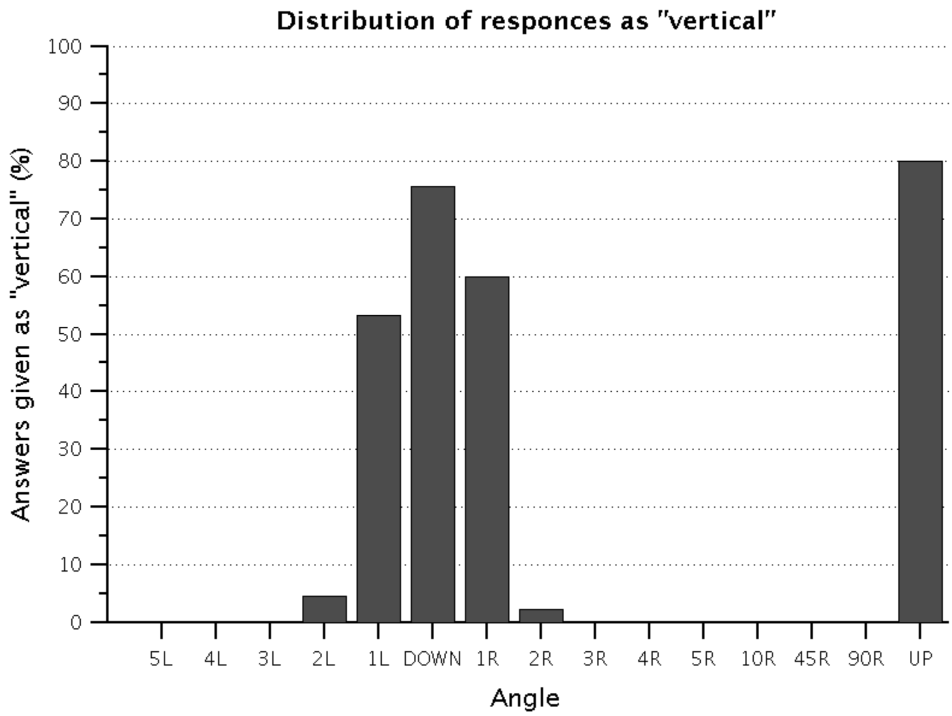


Figure 4-2. The percentage of responses of ‘vertically down’ given for each target direction.

4.3.2 Grouped performance (the effect of physics expertise on total score)

The effect of physics expertise on the ability to answer correctly was examined using Pearson's Chi-squared Test. The number and percentage of correct/incorrect responses are shown in Table 4-1.

Table 4-1. Number and percentage of correct/incorrect scores for novice and expert groups.

	Novice group		Expert group	
	no. responses	%	no. responses	%
Correct	239	88.52	356	87.90
Incorrect	31	11.48	49	12.10
Total	270	100	405	100

There was no significant association between participants' amount of physics knowledge/understanding of physics (expert vs. novice group) and whether they could correctly identify the direction of target movement ($X^2(1)=2.476$, $p=.116$).

4.3.3 Effect of physics expertise on distribution of errors

The performance of participants, split by expertise, is shown in Table 4-2. Examination of Table 4-2 reveals:

1. For each angle, a similar percentage of correct answers was given by both groups with the exception of errors at 4° left/right and 2° right. At 4° left/right the errors were entirely due to the expert group and at 2° right the errors were entirely due to the novice group.
2. Where vertically descending trajectories were marked as incorrect there was a similar percentage of answers declaring it was left or right in both groups. Interestingly a greater percentage of novices declared a descending trajectory to be rightwards than did experts, and a greater percentage of experts declared a descending trajectory to be leftwards than did novices.

Table 4-2. Percentage of correct answers for all directions and, where answers were incorrect, the percentage of responses left/down/right is given. Data is split by physics expertise. Single occurrence in novice group = 5.56%. Single occurrence in expert group = 3.70%.

			Where incorrect:					
	% Correct		% Thought left		% Thought vertical		% Thought right	
Angle	Novice	Expert	Novice	Expert	Novice	Expert	Novice	Expert
5L	100.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
4L	100.00	88.89	0.00	0.00	0.00	0.00	0.00	11.11
3L	100.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
2L	94.44	96.30	0.00	0.00	5.56	3.70	0.00	0.00
1L	44.44	48.15	0.00	0.00	55.56	51.85	0.00	0.00
DOWN	77.78	74.07	5.56	14.81	0.00	0.00	16.67	11.11
1R	33.33	44.44	0.00	0.00	66.67	55.56	0.00	0.00
2R	94.44	100.00	0.00	0.00	5.56	0.00	0.00	0.00
3R	100.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
4R	100.00	88.89	0.00	11.11	0.00	0.00	0.00	0.00
5R	100.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
10R	100.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
45R	100.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
90R	100.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
UP	83.33	77.78	16.67	22.22	0.00	0.00	0.00	0.00

4.4 Discussion

Overall, there was no statistical or observable difference between physics experts and novices regarding their ability to discriminate whether a target was moving vertically, or whether there was some horizontal component to the target's linear motion. The fact that physics expertise yielded no difference in performance suggests that performance is determined by experience of seeing things fall in the real world under gravity, rather than intellectual understanding of gravity.

There are several features in the pattern of errors for the ungrouped data (a pattern shared by the grouped data) that deserve comment. On three occasions when the target was moving 4º right of vertical, it was marked as moving to the left; and on a further three occasions a target moving 4º left of vertical was marked as moving to the right. I consider these errors (when the target was descending at 4º from the vertical) to be anomalous, firstly because there were no errors at 3º or 5º, and secondly because deviations greater than 3º seemed, in the experimenter's judgement, to be obvious. These errors were from a single participant, suggesting possible confusion or a transcription error on their part.

When declaring the direction for an ascending trajectory all errors (20% of answers) were declared leftwards. An anti-clockwise rotation caused by technical error could have created this effect, but this is unlikely for the following reasons. The image signalled to the projector was written and checked in specialist software (see Chapter 2 Methods 2.2.5 and Appendix 7.3.2), so the source of images was true as regards horizontal and vertical directions. Prior to every experimental session, the projected vertical and horizontal was checked using a spirit level, so the projected images were also true. Further, if there were a technical error, there are several features that should present in the data that do not:

- It would be clearer that the 1º rightwards trajectory was rightwards and the 1º leftwards trajectory would appear to be closer to vertically down or even rightwards if any error exceeded 1º. This means that there would be more correct declarations for 1º rightwards moving targets than 1º leftwards targets, and that there should be more declarations of vertically down for targets that were actually moving 1º leftwards than, than declarations of vertically down for targets moving 1º rightwards.
- More vertically down trajectories would be declared rightwards than leftwards.

From the practical and theoretical considerations above, I exclude technical error as an explanation for the results when the target was moving vertically upwards. Therefore, it appears that participants believed a vertically ascending target had a leftwards component to its movement. One possibility is that participants wrongly considered that an ascending target was simply doing the 'opposite' of what the majority of the other targets had done. It is correct to say that an ascending target is doing the opposite of a descending target. However, the majority of descending target movements that participants encountered also had a rightwards component (8 directions were to the right compared with 5 to the left). Furthermore, deviations to the right were sometimes large (10º, 45º and 90º) but due to space limitation, such large deviations could not be matched on the left.

The larger and more frequent deviations to the right for descending targets, might bias participants to expect ascending targets to move to the left if they generalised their expectation of 'opposite' motion – applying it not just to the vertical component (up vs. down), but also to the horizontal component (left vs. right). Such a general expectation of 'opposite' for the ascending target, such that participants might also expect it to move leftwards, is compatible with the observation that in 20% of cases they believed it did so, whereas the target was never reported as moving to the right.

The most important finding of this study is that a target moving at 1º left/right of vertical was more likely to be declared as vertically down than answered correctly. When the target was descending at only 1º left or right of the vertical >50% answers were that the trajectory was vertical with the remainder being correct. This demonstrates a bias for believing that a target descends vertically even when there is visual information to the contrary (each target movement was viewed three times before answering). Although 24.2% of answers for vertically descending targets were declared left (11.1%) or right (13.3%) this error was made in a small minority of cases, in contrast to mistaken description as vertical motion for targets descending 1° left or right which occurred for a majority of trials. For targets falling with a small angular deviation away from vertical, there was therefore a bias to believe those targets were falling vertically.

Previously it has been found that, when reporting the final position of a target that was moving in a straight line before disappearing, participants will report the target to be ahead of its true position (Finke et al., 1986; Finke & Freyd, 1985; Hubbard & Bharucha, 1988; Hubbard, 1990; Nagai et al., 2002) and will apply an effect of gravity on that trajectory (Hubbard & Bharucha, 1988; Nagai et al., 2002) in that the distance ahead for ascending targets will be less than for descending targets, and horizontally moving targets will be reported to be lower than they actually were. Such an effect of gravity appears to have been taken into account at some level when participants were declaring the direction of motion for targets descending at 1° left or right of the vertical.

4.5 Further Work

A second experiment examining the judgement of acceleration amplitude is described in Chapter 5 and represents for Chapter 3 what this chapter represented for Chapter 2 - i.e. participants answer whether a descending target accelerated at less than *g*, at *g* or at greater than *g* after watching a stimulus triplet.

4.6 References

Finke, R. A., & Freyd, J. J. (1985). Transformations of visual memory induced by implied motions of pattern elements. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *11*(4), 780–794.

Finke, R. A., Freyd, J. J., & Shyi, G. C. (1986). Implied velocity and acceleration induce transformations of visual memory. *Journal of Experimental Psychology: General*, *115*(2), 175–88.

Hubbard, T. L. (1990). Cognitive representation of linear motion: possible direction and gravity effects in judged displacement. *Memory & Cognition*, *18*(3), 299–309.

Hubbard, T. L., & Bharucha, J. J. (1988). Judged displacement in apparent vertical and horizontal motion. *Perception & Psychophysics*, *44*(3), 211–21.

Nagai, M., Kazai, K., & Yagi, A. (2002). Larger forward memory displacement in the direction of gravity. *Visual Cognition*, *9*(1/2), 28–40.

CHAPTER 5 CONSCIOUS DISCRIMINATION OF TARGET ACCELERATION AMPLITUDE AND THE EFFECT OF PHYSICS EXPERTISE

In the preceding three experimental chapters, I have found evidence in favour of an internal model of gravity where performance worsens as target kinematics differ increasingly from natural free-fall – such a pattern of errors would arise in the presence of an internal model of gravity. Studies of the interception of free-falling targets often show motor control informed by an internal model of gravity that operates when the visual stimulus is congruent with natural motion. We are able to recognise when virtual targets move unnaturally or when the kinematics of a bouncing ball are unnatural, and in Chapter 4 I found conscious perception of target direction that was apparently influenced by an internal model of gravity. It is unknown whether conscious perception of the rate of target acceleration can be similarly informed. I asked participants to answer whether virtual targets were accelerating at *g* (9.81 m/s^2), slower than *g* or faster than *g*. Targets descended from stationary for ~2.5 m with accelerations of 50%, 75%, 90%, 95-105% (in 1% increments) and 110% of *g*. Data were analysed by grouping participants as physics experts or novices, and as an ungrouped set. Ungrouped data revealed that discrimination of acceleration was poor for all acceleration amplitudes tested apart from 50% of *g*. Performance was better for greater than *g* accelerations than for less than *g* accelerations suggesting participants were more inclined to accept naturally possible free-fall accelerations (at *g* or more slowly) than they were impossibly fast accelerations (great than *g*) that are unlikely to ever be seen. Physics expertise yielded no statistical difference in performance though experts were better than novices at spotting unnaturally fast (greater than *g*) accelerations. Further work with amendment to study design is recommended to investigate this.

5.1 Introduction

Humans are poor at estimating arbitrary accelerations of moving targets (Brouwer, Brenner, & Smeets, 2002; Todd, 1981; Werkhoven, Snippe, & Toet, 1992), and do not account for such accelerations when timing interceptions (Port, Lee, & Georgopoulos, 1997; Zago et al., 2004). However, the human visual system does discriminate between gravitational (9.81m/s^2) and arbitrary accelerations (Indovina et al., 2005) allowing accurately timed interceptions of targets falling under gravity (McIntyre et al., 2001; Zago et al., 2004, 2005) and tracking that is most accurate when target kinematics are close to natural free-fall (descending vertically down (Chapter 2) and accelerating at 99% of g (Chapter 3)). This can be attributed to an internal model of the particular direction and rate of acceleration due to gravity.

Humans can identify a 'natural' bounce compared to a bounce with 'unnatural' kinetics (Twardy & Bingham, 2002), and visual attention in babies is greater for natural gravitational motion than it is for unnatural gravitational motion (Kim & Spelke, 1992) indicating an awareness specifically of natural motion. The operation of an internal model is not something of which we are consciously aware. But the identification of natural movement is what feels consciously appropriate. Koziol et al. (2013) suggest that cognitive processes (as opposed to sensory and motor processes) can be informed by internal models output. However, it is not known whether such information is consciously available. I therefore investigated whether conscious awareness and discrimination of natural movement is informed by the *subconscious* operation of an internal model of the specific rate of acceleration due to gravity, g.

We used the stimuli described in Chapter 3 (targets descending vertically in a straight line and accelerating at either g, faster than g or slower than g). The target was a 15 cm diameter ball and had a long travel distance (with some part of the target still visible, the centre of the target could travel 2.475 m [see Chapter 3: Methods 3.2]). Participants were asked to report whether target acceleration was at g (9.81 m/s^2), less than g, or greater than g.

Previous studies have shown discrimination between arbitrary and gravitational acceleration (Port et al., 1997; Zago et al., 2004), the tracking experiments reported in this thesis have shown preferred accelerations (in terms of lowest errors) around g, and our preceding study (Chapter 4) found some mis-perception of vertically descending motion for targets falling at g but actually at 1° from vertical. Therefore in the current experiment I expect an essentially parallel finding: that targets falling at accelerations close to *g* will be wrongly perceived as *g*, and those accelerations much greater or less than *g* will be correctly perceived as such

5.2 Methods

5.2.1 Participants

Sixteen subjects participated (9 male, 7 female, mean age ± SD: 29.2 ± 6 years) in this experiment. Six subjects were classed as 'experts' (3 male, 3 female, mean age ± SD: 29.8 ± 5 years) having studied physics beyond an UK GCSE level and ten, who had not, were classed as 'novices' (6 male, 4 female, mean age ± SD: 28.6 ± 7). All participants reported normal or corrected to normal vision (using contact lenses), no neurological or sensorimotor disorders, and gave informed consent prior to participation. Experimental procedures were approved by the local ethics committee.

5.2.2 Experimental setup and stimuli

Stimuli and the apparatus were the same as described in Chapter 3, though gaze and marker tracking apparatus and their associated paraphernalia were not employed.

5.2.3 Task

The same stimuli used in Chapter 3 were used in this experiment. Following each triplet (3 identical target motions) participants declared on a questionnaire whether they thought that the target accelerated at *g*, slower than *g* or faster than *g*.

5.3 Results

N.B. I follow the shorthand convention for describing the amplitude of acceleration that was used in Chapter 3 (e.g. an acceleration of '50% of g' is referred to as 'g50').

5.3.1 Un-grouped performance

The performance of participants is shown in Figure 4-1. The percentage of correct answers is shown (wide grey bars) and, where answers were incorrect, the percentage of responses for the given type of error is shown (narrow red/green/yellow bars).

Performance (correct answers – grey bars) was poor for all amplitudes of acceleration apart from for the slowest – g50 (Figure 4-1). At this acceleration there were no reports of faster than *g* acceleration though 16.7% of answers were that the target accelerated at g. There were typically more correct responses for target accelerations at g and accelerations greater than g than there were for accelerations less than g, indicating that accelerations greater than g were more likely to be perceived as such than accelerations less than g were perceived to be slower than g (Figure 4-1).

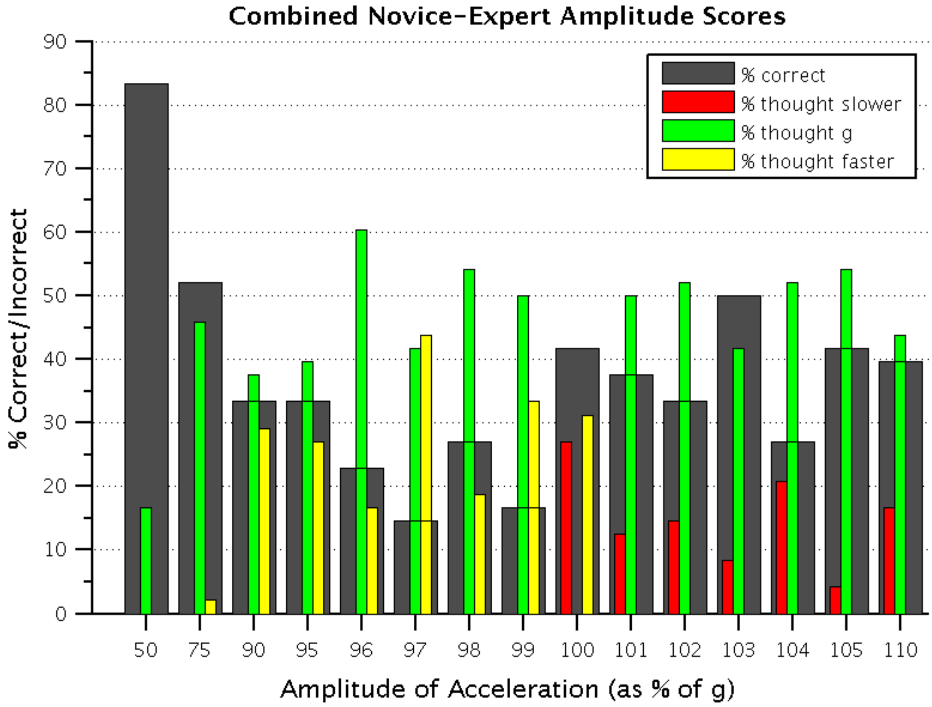


Figure 5-1. Percentage of correct answers for target amplitudes and, where answers are incorrect, the percentage of responses given for other amplitudes (< *g* / *g* / > *g*) is shown.

5.3.2 Grouped performance (the effect of physics expertise on total score)

The effect of physics expertise on the ability to answer correctly was examined using Pearson's Chi-squared Test. The number and percentage of correct/incorrect responses are shown in Table 4-1.

Table 5-1. Number and percentage of correct/incorrect scores for novice and expert groups.

	Novice group		Expert group	
	no. responses	%	no. responses	%
Correct	158	35.11	108	40.00
Incorrect	292	64.89	162	60.00
Total	450	100	270	100.00

There was no significant association between participants' amount of physics knowledge/understanding of physics (expert vs. novice group) and whether they could correctly identify the amplitude of target acceleration ($X^2(1)=1.731$, $p=.188$). The small sample size (6 experts and 10 novices) would not affect this statistical test because of the large number of responses (720) recorded (Field, 2009).

5.3.3 Effect of physics expertise on distribution of errors

The performance of participants, split by expertise, is shown in Table 4-2. Examination reveals that the expert and novice groups performed similarly though, for accelerations greater than *g* experts tended to give more correct responses than novices did.

Table 5-2. Percentage of correct answers for all directions and, where answers were incorrect, the percentage of responses < *g* / *g* / > *g* is given. Data is split by physics expertise. Single occurrence in novice group = 3.33%. Single occurrence in expert group = 5.56%.

			Where incorrect:					
Acc.	% Correct		% Thought < *g*		% Thought *g*		% Thought > *g*	
(% g)	Novice	Expert	Novice	Expert	Novice	Expert	Novice	Expert
50	86.67	77.78	0.00	0.00	13.33	22.22	0.00	0.00
75	56.67	44.44	0.00	0.00	40.00	55.56	3.33	0.00
90	23.33	50.00	0.00	0.00	40.00	33.33	36.67	16.67
95	33.33	33.33	0.00	0.00	40.00	38.89	26.67	27.78
96	20.00	27.78	0.00	0.00	63.33	55.56	16.67	16.67
97	13.33	16.67	0.00	0.00	43.33	38.89	43.33	44.44
98	20.00	38.89	0.00	0.00	63.33	38.89	16.67	22.22
99	20.00	11.11	0.00	0.00	46.67	55.56	33.33	33.33
100	43.33	38.89	26.67	27.78	0.00	0.00	30.00	33.33
101	36.67	38.89	16.67	5.56	46.67	55.56	0.00	0.00
102	33.33	33.33	10.00	22.22	56.67	44.44	0.00	0.00
103	40.00	66.67	6.67	11.11	53.33	22.22	0.00	0.00
104	26.67	27.78	20.00	22.22	53.33	50.00	0.00	0.00
105	36.67	50.00	6.67	0.00	56.67	50.00	0.00	0.00
110	36.67	44.44	20.00	11.11	43.33	44.44	0.00	0.00

5.4 Discussion

There was no significant difference between physics 'experts' and 'novices' regarding their ability to correctly identify whether target accelerations were *g* (9.81m/s^2), less than *g* or greater than *g*. This parallels the finding of Chapter 4 that physics expertise has no effect on correctly identifying the direction of target motion. Both of these results indicate that the internal model of gravity identified elsewhere (Chapters 2 and 3) is not significantly informed by *academic understanding* of physical laws. Rather our findings support the suggestion that internal models are developed and modified from *actual experience* of performing tasks. During performance, predicted motor or sensory outcomes are compared to actual outcomes (Blakemore et al., 1998; Vetter & Wolpert, 2000). Where the predicted outcomes match feedback the models are consolidated and feedback is attenuated but where prediction does not meet feedback the 'sensation' becomes salient (Bays, Flanagan, & Wolpert, 2006; Bays et al., 2005;

Blakemore et al., 1999, 1998; Miall et al., 2007; Shergill et al., 2003), supplementary motor commands can be issued (Bastian, 2006) and the model is modified for future use.

There is a difference between the novice and expert groups' percentage of answers that were correct for accelerations of 101g to 110g (Table 4-2). In this range, experts scored more than novices apart from at 102g where the groups scored the same. This suggests that experts might be more attuned than novices to spotting 'impossible'/'unnatural' faster than *g* accelerations. These differences are small, however a repeat of this experiment with larger sample sizes is required in order make any strong claim concerning a difference between novice and expert physicists in perception of acceleration, particularly within this range of unnaturally fast accelerations.

The distribution of correct answers in the ungrouped data (Figure 4-1 grey bars) is fairly uniform though correct responses appear more likely to be made for acceleration of 100g to 110g than they were 90g to 99g. It is the case that the better perception of faster than *g* accelerations is contributed more by the experts than the novices (see preceding paragraph). This asymmetry suggests that *g* accelerations and faster than *g* accelerations were more accurately perceived than slower than *g* accelerations. Participants may have perceived slower than *g* accelerations as 'normal gravity' because we often see real free-fall accelerations that are less than *g* due to drag. Participants should never see faster than *g* free-fall accelerations so perhaps they were inclined to perceive that these accelerations were not 'normal' i.e. were faster than *g* and respond as such.

Poor performance overall is in contrast to the parallel experiment in Chapter 4 in which discrimination of target direction was good when targets moved at > 1 º from the vertical.

The highest percentage of correct responses was at 50g. This is very slow (4.905 m/s^2) and, to the authors at least, appears very unnatural. I therefore believe that this acceleration in particular may not have been 'tolerated' as I suggested for accelerations between 90g and 99g, but rather was obviously slower than *g*. Participants' responses reflected this. The next highest percentage of correct answers was when viewing a target accelerating at 75g and, at this acceleration, the percentage of correct responses and responses of 'at *g*' were roughly equal (52.08% correct, 45.83% thought *g* and 2.08 thought >*g*). This suggests that accelerations of 75% of *g* might be around the threshold for tolerating seen accelerations as 'natural' (as was the case for accelerations at 90-99% of *g*).

The current study identified possible differences in the perception of unnaturally fast accelerations between expert (physics education beyond UK GCSE) and novice (physics education up to UK GCSE) groups though such differences were not significantly different so further work into any differences is required (see section 5.5). I did find some overall difference in the perception of acceleration: that it is easier to identify unnaturally fast free-fall accelerations (accelerations > *g*) than it is accelerations that are naturally possible in free-fall (accelerations at, or below, *g*) though statistical testing was not possible and should be addressed in further work. I suggest that naturally possible free-fall accelerations are tolerated because they are encountered in the real world whereas those that are unnaturally fast stand-out as such because they are not.

5.5 Further Work

The sample size for this experiment was small (6 'experts' and 10 'novices') and the actual academic understanding of physics for each group was not set. The novice group contained all those with physics education up to the equivalent of the UK GCSE whereas the physics group contained all those with any more academic education in physics regardless of the academic level obtained. For example, the expert group could contain 'experts' ranging from those who studied physics to UK AS level (one year beyond UK GCSE) to those who studied physics for a bachelor's degree or an even greater level. Also, in the UK physics education is mandatory up to GCSE but the grades achieved can vary from top marks to a fail. Though no significant differences were found between the test 'experts' and 'novices', we were not able to entirely rule out differences – experts were better than novices at spotting unnaturally fast (>*g*) accelerations. It may, therefore, be profitable to repeat this experiment with large groups that are clearly defined by level of attainment in physics in order to determine whether the internal model of gravity (identified in Chapters 2, 3 and 4 of this thesis) can contribute to perception of gravitational acceleration. For example a group of novices with a maximum physics education equivalent to UK GCSE graded 'A' or 'B' compared to a group of experts with a maximum physics education of a bachelors degree graded '1st' or '2-1'. These groups should be age matched to ensure that, whilst groups would differ in academic understanding, they would not differ in physics understanding developed in non-academic ways e.g. from experience of the real-world.

Unfortunately it was not possible to test the grouped or ungrouped responses at each individual amplitude of acceleration for significant difference. This was an oversight in the design of the study and during analysis I was not able to identify a statistical test for which these data met the assumptions required. Future work using similar stimuli should consider restricting response options to ‘less than *g*’ and ‘greater than *g*’ (no option of ‘at *g*’) for all acceleration presentations including that of *g*. Given the responses in the current experiment were more correct for accelerations greater than *g*, I expect a ratio of ‘less than *g*’ to ‘greater than *g*’ responses to present similar to a cubic curve as accelerations approach then exceed *g*.

5.6 References

Bastian, A. J. (2006). Learning to predict the future: the cerebellum adapts feedforward movement control. *Current Opinion in Neurobiology*, *16*(6), 645–9.

Bays, P. M., Flanagan, J. R., & Wolpert, D. M. (2006). Attenuation of self-generated tactile sensations is predictive, not postdictive. *PLoS biology*, *4*(2), e28.

Bays, P. M., Wolpert, D. M., & Flanagan, J. R. (2005). Perception of the consequences of self-action is temporally tuned and event driven. *Current Biology*, *15*(12), 1125–8.

Blakemore, S. J., Frith, C. D., & Wolpert, D. M. (1999). Spatio-temporal prediction modulates the perception of self-produced stimuli. *Journal of Cognitive Neuroscience*, *11*(5), 551–9.

Blakemore, S. J., Wolpert, D. M., & Frith, C. D. (1998). Central cancellation of self-produced tickle sensation. *Nature Neuroscience*, *1*(7), 635–40.

Brouwer, A.-M., Brenner, E., & Smeets, J. B. J. (2002). Perception of acceleration with short presentation times: can acceleration be used in interception? *Perception & Psychophysics*, *64*(7), 1160–8.

Field, A. (2009). *Discovering Statistics Using SPSS* (Third.). London: SAGE Publications.

Indovina, I., Maffei, V., Bosco, G., Zago, M., Macaluso, E., & Lacquaniti, F. (2005). Representation of visual gravitational motion in the human vestibular cortex. *Science*, *308*(5720), 416–9.

Kim, I. K., & Spelke, E. S. (1992). Infants’ Sensitivity to Effects of Gravity on Visible Object Motion. *Journal of Experimental Psychology: Human Perception and Performance*, *18*(2), 385–393.

Koziol, L. F., Budding, D., Andreasen, N., D’Arrigo, S., Bulgheroni, S., Imamizu, H., … Yamazaki, T. (2013). Consensus Paper: The Cerebellum’s Role in Movement and Cognition. *Cerebellum*.

McIntyre, J., Zago, M., Berthoz, A., & Lacquaniti, F. (2001). Does the brain model Newton’s laws? *Nature Neuroscience*, *4*(7), 693–4.

Miall, R. C., Christensen, L. O. D., Cain, O., & Stanley, J. (2007). Disruption of State Estimation in the Human Lateral Cerebellum. *Cerebellum*, *5*(11), 2733–2744.

Port, N. L., Lee, D., & Georgopoulos, a P. (1997). Manual interception of moving targets I. Performance and movement initiation. *Experimental Brain Research*, *116*(3), 421–33.

Schmitz, C., Martin, N., & Assaiante, C. (1999). Development of anticipatory postural adjustments in a bimanual load-lifting task in children. *Experimental Brain Research*, *126*(2), 200–4.

Schmitz, C., Martin, N., & Assaiante, C. (2002). Building anticipatory postural adjustment during childhood: a kinematic and electromyographic analysis of unloading in children from 4 to 8 years of age. *Experimental Brain Research*, *142*(3), 354–64.

Shergill, S. S., Bays, P. M., Frith, C. D., & Wolpert, D. M. (2003). Two eyes for an eye: the neuroscience of force escalation. *Science*, *301*(5630), 187.

Todd, J. T. (1981). Visual information about moving objects. *Journal of Experimental Psychology: Human Perception and Performance*, *7*(4), 975–810.

Twardy, C. R., & Bingham, G. P. (2002). Causation, causal perception, and conservation laws. *Perception & psychophysics*, *64*(6), 956–68.

Vetter, P., & Wolpert, D. M. (2000). The CNS updates its context estimate in the absence of feedback. *Neuroreport*, *11*(17), 3783–6.

Werkhoven, P., Snippe, H. P., & Toet, a. (1992). Visual processing of optic acceleration. *Vision research*, *32*(12), 2313–29.

Zago, M., Bosco, G., Maffei, V., Iosa, M., Ivanenko, Y. P., & Lacquaniti, F. (2004). Internal models of target motion: expected dynamics overrides measured kinematics in timing manual interceptions. *Journal of Neurophysiology*, *91*(4), 1620–34.

Zago, M., Bosco, G., Maffei, V., Iosa, M., Ivanenko, Y. P., & Lacquaniti, F. (2005). Fast Adaptation of the Internal Model of Gravity for Manual Interceptions: Evidence for Event-Dependent Learning. In *Journal of Neurophysiology* (pp. 1055–68).

CHAPTER 6
EXPLORING DATA INCONSISTENCIES, MAIN THESIS FINDINGS & CONCLUSIONS

The overall aim of this research programme was to investigate the existence of a possible internal model of gravity, and to explore its directional and acceleration amplitude aspects. To achieve this I conducted three experiments that are described in chapters 2, 3 and 4 of this thesis. In this chapter, the methods and main findings of these studies are outlined followed by a brief statement of overall conclusions. First I briefly report on possible alternative theories of motor control and how they may apply to the data presented in this thesis

6.1 Exploring data inconsistencies

The data presented in this thesis support the concept of an internal model of gravity when considered overall. However, whilst not supporting the other principle alternative in predictive motor control for interaction with a freely moving object (direct perception – see sections 1.2.4 and 1.2.5), some individual pieces of data do not support the internal model hypothesis. I will now briefly discuss three possibilities on the source of this inconsistency.

i) Internal model flexibility and malleability. I have stated previously that an internal model of gravity (that can predict the future position in time of a free-falling target) is thought to be flexible and malleable to accommodate the variety of target kinematics experienced in daily life (section 1.2.2). An exaggerated example of quite different free-fall kinematic behaviour is the comparison of a bowling ball to a beach ball. The model's flexibility should allow the kinematic behaviours of the bowling ball and beach ball to be predicted. However, the drive of the model to greater real-world application results in adaptation to common experiences weighted towards the most recent ones meaning that lots of recent interaction with a beach ball should result in poorer predictive interaction with a bowling ball and vice-versa. Adaptation in the studies presented in this thesis may result in skewed 'default' values (the hypothesis being a ‘default’ model is tuned to vertically down and acceleration at *g*) if a series of conditions arose with similar but unnatural elements e.g. presentation of accelerations from 99 to 95% of *g* then presentation of acceleration from 101 to 105% of *g*. Though randomised condition orders were employed, there was no counterbalancing because of the number of participants required to achieve this. Perhaps with greater participant numbers and/or counterbalanced conditions the inconsistencies in data would evaporate.

ii) Bayesian selection of a prediction mechanism. Another explanation for the inconsistencies may be whether any internal model was even active during a particular condition. The 'selection' or 'activation' of the model may be based on Bayesian probabilities – the expression of the world in terms of probability. In sequential analysis, a component of Bayesian inference, the probability estimate of hypotheses are updated as more evidence is acquired. The acquisition of visual information on free-falling trajectories can be thought of in such a way i.e. are the observed kinematics *most likely* to result from gravity *or* from some other dynamic? If the answer is gravity then the model should output prediction of future position but if the answer is otherwise then the CNS may consider alternative possibilities, rely on feedback, direct perception or on some other mechanism. In fact Bayesian selection is, in a way, similar to direct perception in that a more correct prediction of future target position can be made as more information is gathered. This allows hypothesis testing in sequential analysis and minimisation of error based on observed velocity in direct perception. However if direct perception were employed by the CNS as an alternative then prediction errors would be uniform in the experiment described in Chapter 2. Though this was not the case, the averaged error shown may be a some combination of predictions formed by direct perception, internal models, feedback or another mechanism.

N.B. Practical application of Bayesian inference suggests that though several hypothesis based on prior experiences can be tested, one or more may be rejected based on prior beliefs. A relevant example is that of releasing an object to 'free-fall' but observing it accelerating vertically upwards at g. The evidence supports a hypothesis that gravity acts upwards but prior belief may dismiss the hypothesis.

iii) Dynamic systems theory. As a constantly moving and changing system the human body can be considered as a dynamic system Even when resting there is a some small internal movement such as the beating heart, fluid flow and digestive processing. Accordingly any method of motor control should consider, to some degree, all forces acting on that system. Unfortunately dynamic systems are not linear and any number of internal or external factors can influence outputs. Each component of a dynamic system should be conceptually considered as an independent module that may or may not be influenced by its contemporaries or by the state of the system as a whole. Consequently as the number components in a system increases the complexity increases and outputs can become unpredictable. The poses a problem for a motor controller so dynamic systems that produce meaningful *emergent* actions are thought of as self-organising. Emergent outputs are a consequence of each component acting together rather than the 'traditional' concept of top-down control. This brief description of dynamic systems theory is adapted from that given in (Edwards, 2010) – a more detailed introduction can be found in that text. The complexity of dynamic systems can clearly complicate interpretations of data from behavioural tasks designed to investigate neural concepts and to the authors knowledge, this theory has not been expanded to predicting future states of *external* stimuli.

I do not dismiss this idea (rather I it found intriguing) but postulation on this idea is beyond the scope of this thesis and so will not be discussed further. For reviews of dynamics systems theory applying to: predictive motor states see Schaal, Mohajerian, & Ijspeert (2007) and Shenoy, Sahani, & Churchland (2013); and to cognitive development see (Spencer, Austin, & Schutte, 2012).

The literature discussion sections of this thesis argue in favour of the existence of internal models for internal and external prediction such as anisotropic force requirements, force-field adaptation and prediction of free-fall. Though I believe that an internal model of gravity provides the best *existing* explanation for the presented data, they are aware that the inconsistency in some of the results may not be entirely due to the noise inherent in this type of behavioural task. Further I acknowledge that in fact it may be due to something 'upstream' of a potential model (such as Bayesian selection or activation an activation threshold) or control by other means (such as some emergent behaviour). It is possible that only one or a combination these suggested explanations could account for the presented data's inconsistencies and it is possible that none of the mentioned possibilities are veracious.

6.2 Main Thesis Findings

Chapter 2 – Directional aspects of an internal model of gravity

Participants tracked stimuli that accelerated naturally at *g* (9.81 m/s^2) and moved with one of 15 straight-line trajectories: ascending vertically, descending vertically, or descending off the vertical at 1-5° [in 1% increments] left and right, 10°, 45°, and 90° right. Tracking was either by finger pointing, laser pointing, gaze tracking in isolation or gaze tracking with concomitant manual or laser tracking. Each stimulus was presented three times sequentially and tracking performed for each. Tracking error (instantaneous difference in tracked position to target position) was calculated perpendicular and parallel to the direction of target motion for every 10 ms for each 730 ms stimulus duration. Error was used as a measure of performance. The main findings are:

- Pointing, from the actor's perspective, is judged by a vector from the dominant eye, past the fingertip and onto the target.
- In the absence of on-screen accurate feedback of indicated position (i.e. non-laser trials), tracking was generally found to be tuned for vertically descending targets, or targets that tended increasingly to vertically downwards movement over time. This indicates that participants were likely to be using an internal model of gravity acting vertically downwards to predict the future position of free-falling targets.
- The laser provided accurate on-line feedback that prompts (or pushes the control mode into) reliance on feedback more than prediction.
- Practice at persistently unnatural trajectories can modify the model but 3 presentations were insufficient to completely reorient any model to the presented direction of motion (there remained differences in errors at the third attempt compared to errors seen when tracking a target moving vertically downwards).
- There was no evidence of 'direct perception'.
- Manual tracking of targets moving at just 1° from the vertical was towards the vertical, indicating an expectation of vertically downwards movement.
- Tracking of targets moving at 2-10° away from vertical was typically similar, suggesting that the directional aspect of the internal model underlying tracking control is broadly tuned over this range.
- For an ascending target, the pattern of errors suggests that there was an

assumption that targets would not accelerate upwards.

- When targets moved 45° from the vertical, tracking was typically parabolic – as though the target was expected to follow a natural trajectory.
- Finger pointing has little or no effect on gaze tracking, whereas when one provides augmented tracking feedback (a laser spot), gaze will follow such feedback rather than the target to be tracked.

Chapter 3 – Amplitude aspects of an internal model of gravity

Participants tracked targets that always moved in a natural straight-line descent vertically downwards, but with one of 15 accelerations: 50%, 75%, 90%, 95-105% [in 1% increments] and 110% of *g* ($9.81 m/s^2$). Tracking methods, presentation protocol and tracking error were the same as described in Chapter 2 but only 690 ms (the total presentation time of the fastest moving target) of each trial was analysed. The main findings are:

1. In the absence of on-screen accurate feedback of indicated position (i.e. non-laser trials), tracking was generally found to be tuned for accelerations at *g* or slightly less than *g* indicating that participants appeared to use an internal model of gravity to predict the future position of free-falling targets.
2. There was no evidence for 'direct perception'.
3. For all tracking methods, the tracked errors were lowest for targets accelerating at 50% and 75% of *g*. Low instantaneous velocities at these accelerations might allow for corrections to tracking movement from on-line acquisition of visual information that contradicts predicted target movement.
4. When manually tracking, there was a noticeable change in tracking error for target accelerations greater than 100% of *g* i.e. tracking output (and control) differed when targets accelerated *unnaturally* quickly. This suggests the existence an internal model of gravity tuned to *g*.
5. Laser tracking was behind and slower than the target for all target accelerations. When tracking accelerations ≥100% of *g*, first attempt errors continued to increase with target acceleration, but second and third attempt errors did not, suggesting firstly that an internal model of gravity was predicting target acceleration not greater than *g*, and secondly that the acceleration amplitude parameter of a possible internal model was partially modified (as found for the directional aspect) with repeated encounter of a novel (unnatural) acceleration.

6. The pattern of saccades for gaze tracking in isolation and in the manual condition suggests an internal model predicted the position of a target based on an expected target acceleration between 90% and 100% of *g*.
7. Gaze tracking in the laser condition followed the laser spot rather the target itself.

Chapter 4 – Conscious discrimination of target path angle, and the effect of physics expertise

The same stimuli and the same presentation protocol as described in Chapter 2 were used, but rather than tracking the target, participants were required to judge whether target trajectories were on the vertical, to the left of vertical or to the right of vertical. Answers were marked on a questionnaire. The main findings are:

1. Small deviations from the vertical (trajectories of only 1° left/right of vertical) were more likely to be reported as on the vertical than answered correctly, demonstrating a bias for believing that a target descends vertically even when there is visual information to the contrary i.e. an effect of normal gravity was expected on observed trajectory.
2. Physics expertise yielded no difference in performance, suggesting that performance, based on an internal model of gravity, is determined by experience of seeing things fall in the real world under gravity rather than intellectual understanding of gravity.

Chapter 5 – Conscious discrimination of target acceleration amplitude and the effect of physics expertise

In this experiment I used the same stimuli and the same presentation protocol as described in Chapter 3. As in Chapter 4, participants were required to make judgements on the stimuli observed rather than track them. In this case answering whether targets accelerated from stationary at less than *g*, at *g*, or greater than *g*. The main findings are:

1. Performance (% correct answers) was generally poor for all acceleration amplitudes apart from that of 50% of *g*. This acceleration is clearly very slow compared to all other observed trajectories.
2. Performance (% correct answers) was better for accelerations < *g* than acceleration > *g* indicating that participants were more inclined to accept naturally possible slow accelerations as ‘real’ than they were unnaturally fast

accelerations.

3. Physics expertise yielded no difference in performance, suggesting that performance, based on an internal model of gravity, is not determined by academic understanding of gravity.

6.3 Conclusions

1. The presented data suggest that the CNS may construct and maintain an internal model of gravity.
2. This internal model would be established on the basis of experience of objects falling naturally under the influence of normal gravity.
3. This internal model is capable of some modification by novel unnatural experiences, of unusual direction or amplitude accelerations.
4. This model may be capable of predicting the future position of free-falling targets and such predictions are generally of movement in a natural 'real-world' manner – acceleration at 99% or 100% of *g* and vertically downwards or in a direction tending increasingly to vertically downwards over time.
5. 'Direct perception' is not used to predict the future position of free-falling targets.
6. Tracking by finger pointing is achieved using a vector from the dominant eye past the pointing fingertip and onto a target.
7. To the author's knowledge these studies are the first to systematically investigate the directional and amplitude aspects of an internal model of *g*.
8. The section 'Further Work' in each experimental chapter (Chapters 2, 3, 4 and 5.) proposes studies that could provide additional insight into the suggested probable internal model of gravity (see also Further Work in 7.1.5).

6.4 References

Edwards, W. (2010). *Motor Learning and Control: From Theory to Practice* (1st ed.). Brooks/Cole.

Schaal, S., Mohajerian, P., & Ijspeert, A. (2007). Dynamics systems vs. optimal control--a unifying view. *Progress in Brain Research*, *165*(1), 425–45.

Shenoy, K. V, Sahani, M., & Churchland, M. M. (2013). Cortical control of arm movements: a dynamical systems perspective. *Annual Review of Neuroscience*, *36*, 337–59.

Spencer, J. P., Austin, A., & Schutte, A. R. (2012). Contributions of dynamic systems theory to cognitive development. *Cognitive Development*, *27*(4), 401–418.

"Gravity is a habit that is hard to shake off."

Terry Pratchett. 'Small Gods' (1992)

CHAPTER 7
APPENDICES

7.1 Pilot: An investigation into any pre-existing internal model of gravity

Studies of internal models of gravity often use interception or tracking but these paradigms present participants with moving targets. This presents a problem because the nature of internal models is to adapt in order to maintain usefulness. So by the presentation of any stimulus relevant to the model there is the possibility of changing the model's characteristics – and the parameters might change easily and rapidly perhaps even within a single trial. I therefore conducted a study to investigate whether any pre-existing model(s) of gravity existed and could be accessed without the presentation of *any* moving stimuli. Participants were presented with a target object shown at two locations connected by an arrow indicating a straight-line direction of motion in which they were to imagine gravity acting on the target. Participants executed tracking of this imagined motion i.e. tracking an imaginary unseen movement of a target accelerating at g (9.81m/s^2) in any given direction. Directions included vertically downwards or upwards, horizontally left or right, or descending left or right at 45º off vertically downwards. Tracking was either by pointing a finger or a laser, gaze tracking alone, or gaze tracking with either finger or laser pointing. Apparent object density was varied to investigate whether there would be recruitment of a particular internal model for each object or whether the parameters of a more general model would simply vary depending on the object type. Targets used were a beach ball, basketball and a bowling ball. This experiment was a pilot for the series of experiments reported in the main body of this thesis. Numerous difficulties (see Appendix 7.3.1) resulted in generally poor data so only the finger pointing and laser pointing from a single participant are analysed and presented here to demonstrate the method and specimen results.

No meaningful effect of tracking method (laser or manual), tracking attempt (first, second or third), or direction of imagined motion (vertically down or up, horizontally left or right, or 45º left or right) was observed. From the limited data available I suggest that use of an internal model of gravity to 'assist' tracking of targets moving freely under gravity, requires the target to be tracked to be seen.

Primarily this study served as a pilot, training the author in setting up and running experiments, and highlighting what changes needed to be made to the experimental protocol, stimuli and apparatus. It was therefore an important stage in the development of the successful studies reported in the main body of this thesis.

7.1.1 Introduction

In my previous studies I have provided evidence that an internal model of gravity is used in visually guided tracking of targets whose kinematics are close to that of free-fall by gravity (Chapters 2 and 3 of this thesis). The use of such a model is widely accepted for seen virtual (Le Séac'h et al., 2010; Senot et al., 2012, 2005) and real stimuli (McIntyre et al., 2001) – in-depth discussion is available in Chapters 1 and 2 of this thesis. What is less well understood is the involvement of the model in more cognitive processes though there is evidence for identification of natural trajectories (Chapter 3 of this thesis), identification of natural bounce (Twardy & Bingham, 2002) and preference for observed gravitational acceleration in infants (Kim & Spelke, 1992). This shows some level of awareness of natural free-fall motion outside of a motor task. In these studies the stimulus is not occluded. However, the use of an internal model with only brief visual stimulation due to target occlusion was recently demonstrated by Zago, Iosa, Maffei, & Lacquaniti (2010) in an interception paradigm. Prediction of the future position of the target without continuous visual stimulation is necessary in such a task. It is not known whether the model can be used when there is no visible movement i.e. the entire movement must be predicted from stationary starting position to final position with acceleration at g (9.81 m/s^2).

Apparent target mass is known to affect responses to target movement when response time is short despite explicit knowledge that such mass would not affect movement in the experimental circumstances (Hubbard, 1997). I therefore introduced a condition where the apparent mass (and density) of the target varied by presenting stimuli either as a bowling ball, a beach ball or a basketball.

We have found that tracking errors reduce with practice (Chapters 2 and 3 of this thesis) though this is not anticipated in the current experiment because here there is no indication of tracking error. As such, I expect tracking errors should remain consistent with angle and ball conditions.

Issues of gravitational and inertial influence on tracking methods have been discussed previously in this thesis (see Chapter 2 Discussion 2.4.4 in particular) and so will not be covered here beyond comment that such influences are not believed to affect tracking movements. The method of tracking by manual pointing is covered in Chapter 2 Results 2.3.1 and Discussion 2.4.2 and will not be covered here.

7.1.2 Methods

7.1.2.1 Participants

21 subjects (15 male, 6 female, mean age ± SD: 26.1 ± 3.6 years) participated in this experiment. All participants reported normal or corrected to normal vision (using contact lenses), no neurological or sensorimotor disorders, and gave informed consent prior to participation. Only data from a single participant is presented here (a male, aged 31, with right eye and right hand dominant). Experimental procedures were approved by the local ethics committee.

7.1.2.2 Determining hand & eye dominance

Hand and eye dominance was determined in the same way as described in Chapter 2 (section 2.2.2).

7.1.2.3 Experimental setup

The experimental setup (equipment used, distances between items etc.) were the same as described in Chapter 2 (Methods 2.2.3) apart from the following differences:

- Data to the projector was provided by an Apple MacBook Pro (OS 10.6.8, 2.26 GHz Intel Core Duo, 4 GB 1067 MHz DDR3 (RAM)) running Microsoft PowerPoint:mac^{2008} (V12.3.6).

- The hand held laser was a red < 5 Mw push button activated cylindrical rifle laser. A custom-made aluminium surround was built to create a flat surface to which Vicon markers were attached (Figure 7-1). The complete unit was 65 mm in length, 25 mm in diameter, weighed 61g and was held like a pen. At 3 m the laser produced a spotlight with a radius of ~1 cm with a faint corona whose visibility varied depending on the ambient light level.

- The laboratory was not lightproof and had large wall and ceiling windows. The experiments were restricted to after sunset on winter evenings and all accessible windows were covered with blackout material to minimise ambient light.

- Seven Vicon cameras were used and these were generally further away from the subject.
- A digital video camera was set up behind participants to record the actual appearance time of the computer generated stimuli on the screen, and to compare that to the timing of key presses that triggered stimulus appearance and change.

Figure 7-1. Laser pointing unit used by participants. < 5 Mw push button activated cylindrical rifle laser in custom surround with Vicon markers attached.

7.1.2.4 Task

Participants were presented with two images of a ball and an arrow between them indicating a straight-line direction of travel (see section 7.1.2.5 Stimuli). Participants were instructed to 'imagine that the ball would fall naturally due to gravity' from its starting stationary location (at the arrow's tail) and through its end location (at the arrow's head) to 'some way off the edge of the screen - as if it could just keep going'. Falling due to gravity was to be imagined regardless of the specified direction of travel. Tracking was either: using gaze only; using gaze together with either laser pointing or manual pointing; or tracking only with laser or manual pointing whilst keeping gaze stationary at the target's starting location.

7.1.2.5 Stimuli

The first stage of a stimulus presentation comprised two identical images of a ball with a diameter of 15 cm that were connected by an arrow indicating a direction of motion (Figure 7-2A). The second stage contained just the target at the start location (Figure 7-2B) and served as a 'ready' signal for participants to prepare tracking along the direction of travel indicated in the previous image by the arrow. The third stage was a blank screen and the 'go signal' to immediately track the imagined 'free-fall' at g (9.81 m/s^2). The participant was told to imagine that the target began to fall at the moment it disappeared.

The direction of motion could be vertical descent or ascent, horizontally left or right, or descending 45º left or right from the vertical (Figure 7-2C). The target's orientation was rotated to match travel direction (Figure 7-2D). The targets were either a bowling ball, a basketball or a beach ball (Figure 7-3).

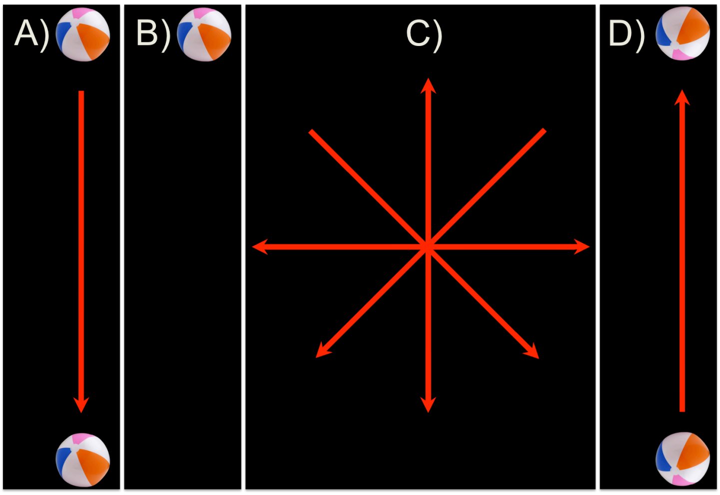


Figure 7-2. A) Example of target and travel direction. B) Example of 'ready' signal for participants. When the screen became completely black this was a 'go' signal for participants to track an imagined 'drop' at *g* (9.81 m/s^2) along the target path given previously. C) Possible travel directions. D) Example of target orientation change for different travel directions.

Figure 7-3. Stimulus objects used. From left to right: beach ball, basketball and bowling ball. Targets were presented with a 15 cm diameter in the experiment.

7.1.2.6 Protocol

For each target, participants tracked each angle three times using each tracking method. Trials were blocked by a random target type, then a random angle and finally a random tracking method. Repetitions of a particular condition occurred sequentially. For each participant 270 trials were obtained (3 targets * 6 directions * 5 tracking methods * 3 repetitions). In the experiment described in Chapter 2, the vertically upwards acceleration was presented last because it was wholly unnatural, and was the only condition in which the target started at the bottom of the screen (all other trials had the identical start location near the top of the screen) but here there was no actual presentation of acceleration, and all start locations depended upon subsequent direction of travel. Therefore, in this experiment the vertically upward direction was included anywhere in the randomised angle order.

A remote trigger, a hidden key pressed by the experimenter, began recording of Vicon marker position and gaze recording, and presented the first stimulus screen (Figure 7-2A). A second key press triggered presentation of the second stimulus screen (Figure 7-2B). A third key press triggered presentation of the third, blank, screen (Figure 7-2C – the ‘go’ signal) and generated a recorded TTL pulse used later to identify trial events.

7.1.2.7 Data analysis

The analysed time period of data was the same as used in the experiments described in Chapters 2 – the first 730 ms (730 samples) of data. For this period, the position of the imaginary target was calculated in the same way as described in Chapter 2 – the target’s centre as accelerating from stationary at 9.81 m/s^2 with zero position change in the first instance.

For these data, only the total and final position, velocity and acceleration errors were calculated since the absolute values of these errors (ignoring the sign) were not informative in the earlier chapters. Only errors for manual and laser tracking have been calculated because of difficulties with the quality of data from the eye tracker (see Appendix 7.3.1.1 and 7.3.1.2). Only in-line errors are examined.

Statistical analysis of the data was not performed because only one subject was available and because, following visual inspection of the time-series and trajectory plots presented later, it was clear tracking errors were very large and appeared to differ little between trajectory angles and attempts.

In Chapters 2 and 3 I conducted data averaging to avoid substantial data loss that would be caused by the listwise deletion employed the statistical tests used for analysis (see Chapter 2 Methods 2.2.9). Though no statistical tests were performed on the current data I have employed the same data averaging on the plots showing total and final errors (though not for the time-series and trajectory plots).

7.1.3 Results

N.B. Time-series and trajectory data are plotted with data up to 1500 ms (solid lines from 1-730 ms and dashed lines from 731-1500 ms). All reference to final errors indicate tracking error at 730 ms and not at 1500 ms unless otherwise stated.

7.1.3.1 Movement initiation

For the current experiment there was no visual or audible countdown as in the experiments described in Chapters 2 and 3. Because there was a random delay between the 'ready' signal and the 'go' and because there wasn't a real target to track, I considered analysing the tracking movements for 730 ms (730 samples) from the moment tracking actually began.

The time of movement initiation was identified by creating a rolling window of 10 samples of the in-line component of tracking (after counter-rotation by tracking angle) and identifying the first instance from which the standard deviation exceeded 10 for a subsequent 50 samples. These values are essentially arbitrary but were identified as a good fit to our data following some systematic investigation. This method consistently indentified what appears to be the correct time of movement initiation whilst avoid the identification of false starts or fluctuations in tracked position – for example see Figure 7-4 where identification of a false start (approximately 500 ms before true tracking begins – red line) is avoided.

However, because the time of movement initiation is variable and because the removal of all screen stimuli was described to participants as the 'go signal' I have taken this time – the 'go signal' – to be time from which the subsequent 730 ms of tracking is analysed.

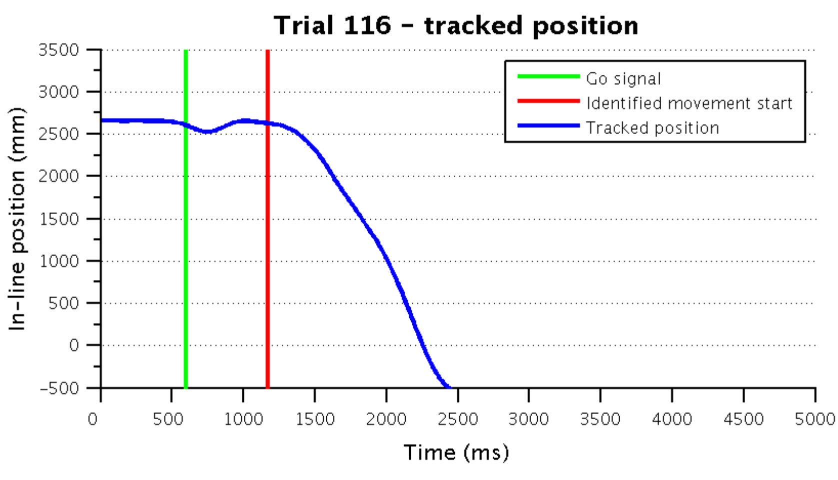


Figure 7-4. Example of the automatic identification of movement initiation. This method avoids the detection of false starts. Blue line: tracked position. Green line: participants 'go' signal. Red line: The time of movement start as identified using our automatic method.

7.1.3.2 Laser tracking along the direction of target movement in the bowling ball condition: time-series plot

N.B. For all time-series and trajectory plots only data from the bowling ball condition is shown. This is the condition that should have elicited the fastest tracking (see

Introduction 7.1.1). These plots are to illustrate the tardy nature of tracking even for this condition.

First I present the time-series of laser in-line tracking position, velocity and acceleration and the tracking errors in those terms. These plots are shown as an example of tracking that was typical for this participant whether tracking in the laser or manual condition. Only the laser condition is presented in this way because a small but variable position offset in tracked position when manual tracking (see section 7.1.3.3.1) makes the averaging together of counter-rotated tracking traces (tracking angle rotated to vertical down) less meaningful than for the laser condition. However, for both the laser and manual conditions, the profile of position, velocity and acceleration (and their errors) were similar and shared the features described below regardless of the ball type (bowling ball, beach ball or basketball) tracked.

Several features are clear in the plot of laser in-line tracking in the bowling ball condition (Figure 7-5):

- Tracking began at approximately zero position error indicating that tracking was 'on target' before the 'go signal'.

- There was a delay of approximately 700 ms before tracking started following the 'go signal'. Tracking did not come close to the velocity or acceleration required to track the target – position and velocity tracking errors increase rapidly for the duration of the shown period because this error results from rapidly changing target position, velocity and acceleration with a relatively stationary tracked position.

- There was no pulse of acceleration as was seen when tracking visible targets in Chapters 2 & 3.

- The vertical position plot shows tracking began earlier with each attempt. Similar position, velocity and acceleration error profiles for each of the three attempts indicate that although tracking began progressively closer to the 'go signal', all tracking movements were alike.

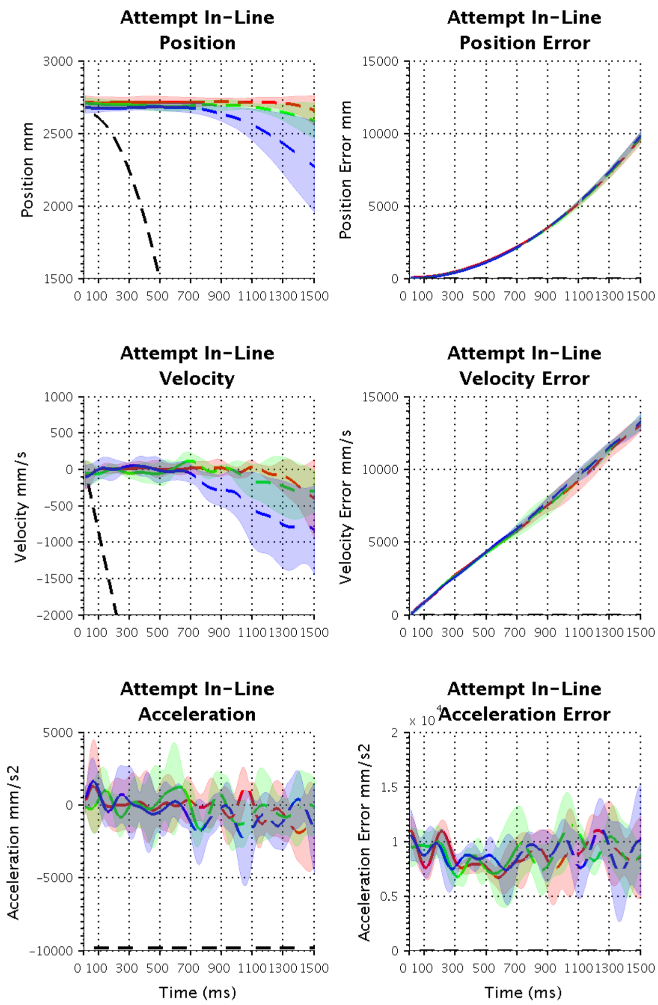


Figure 7-5. Time series of laser tracked in-line position, velocity and acceleration for each attempt at the bowling ball condition. The thick red, green and blue lines are the mean values for first, second and third attempt and corresponding coloured shading indicates the SD. All angles are pooled.

7.1.3.3 Manual tracking

7.1.3.3.1 Manual tracking: Trajectory plots

Tracking failed to keep up with the movement of the unseen target – tracked location from 1 to 730 ms (Figure 7-6 solid red, green and blue lines) covered only a fraction of the required distance and, even up to 1500 ms (dashed red, green and blue lines) tracking did not cover the distance that the target would drop in 730 ms. Tracking did not differ consistently between condition angles, though starting tracked position (at 1 ms) was offset differently depending on the condition angle. This was probably not an actual error in pointing by the subject, because accurate start locations were found in the laser pointing condition (Figure 7-9); this offset is likely to be related to technical issues in the method of tracking.

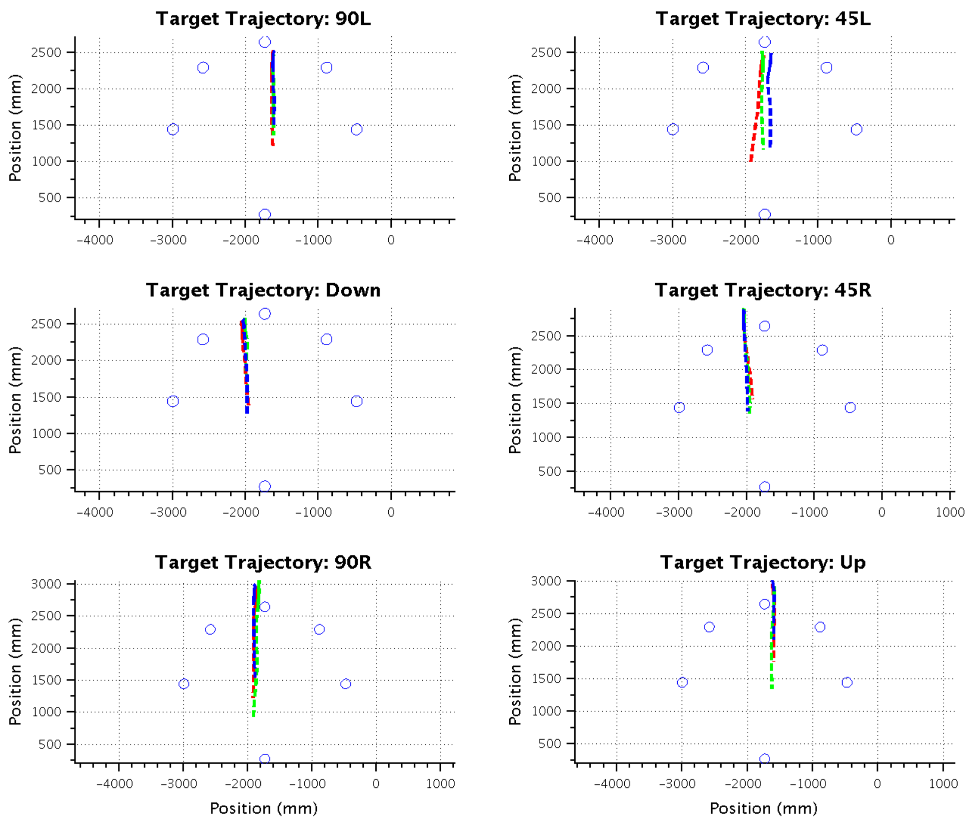


Figure 7-6. Trajectory plots of manual tracking of each ball in each angle condition. Mean tracked position of three attempts for bowling ball, basketball and beach ball are shown in red, green and blue (respectively). Solid lines show the first 730 ms of tracking and dashed lines show tracking from 730 to 1500 ms. Target start positions and radius are shown as blue circles. All trajectories are rotated to a common start position.

7.1.3.3.2 Manual tracking: Time-series of tracked position error for individual target directions

The time-series of vertical position error from 1 to 730 ms show an increasing error from within ±500 mm error to approximately 2500 mm error. The error increase is smooth and featureless for all angles and so this data plot is not shown. The horizontal position error is also feature less and again is not shown. There is some sideways error but this does not change over the analysed time period.

Since this participant did not begin tracking until around 700 ms after the target started to move, errors within that time frame simply reflect target motion away from the stationary start point. From 700 ms up to 1500 ms the participant was still tracking very slowly, so tracking error continued to be generated mainly by the much more rapid target movement.

7.1.3.3.3 Manual tracking: The effect of target angle on tracking

Total and final position errors show that tracking in any direction was behind the target for all target types (Figure 7-7). Total and final position errors show similar profiles. The standard deviation of errors for each target angle appears not to be related to the angle difference from vertically down. At each angle the mean error (of three tracking errors) are similar for all ball types and there does not appear to be a consistent pattern to the errors between angles. For example, the tracking errors for 90º leftwards, 45º rightwards and vertically up are similar, as are those for 45º leftwards, vertically downwards and 90º rightwards.

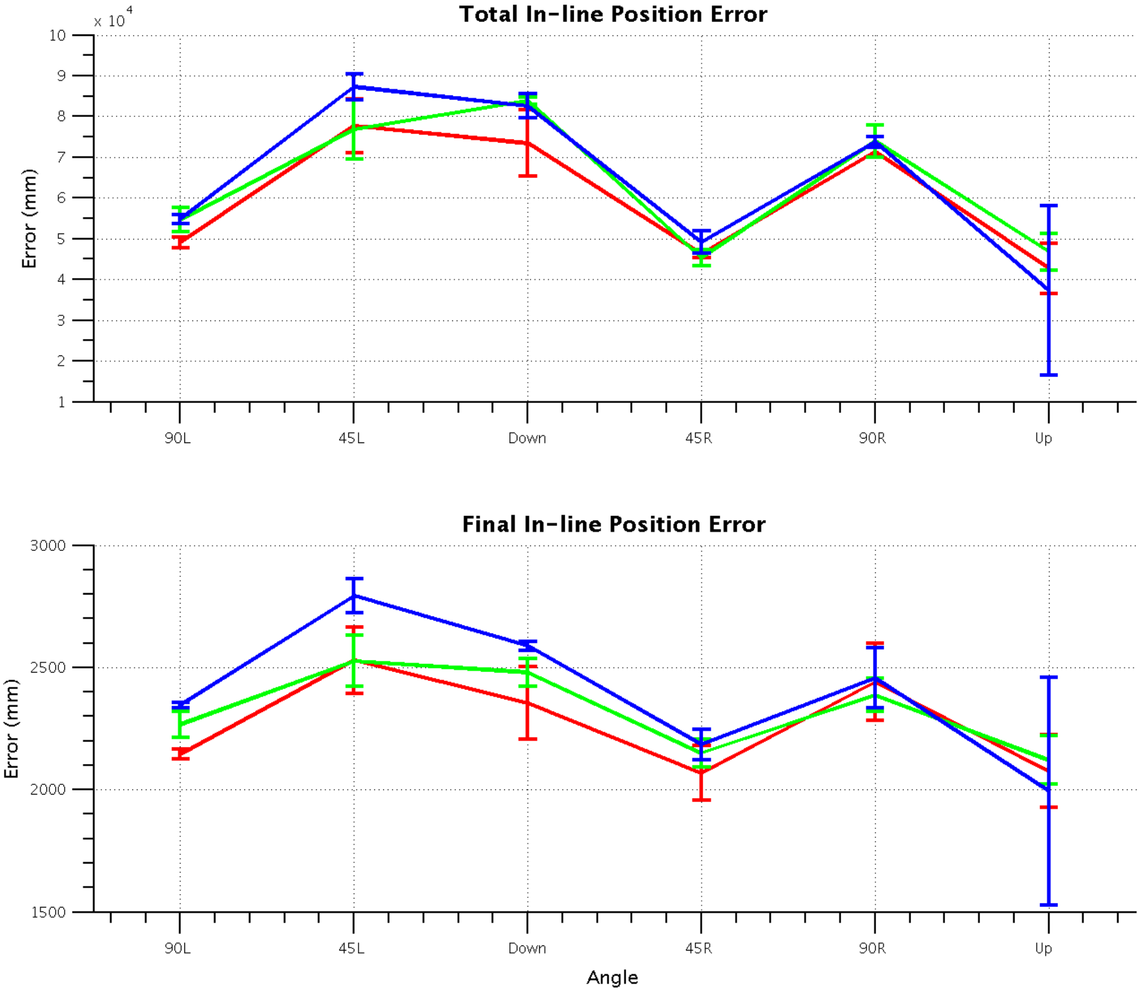


Figure 7-7. Manual tracking mean total and final errors (with SD) along the line of target motion for different directions (angles). Tracking of the bowling ball, basketball and beach ball are show in red, green and blue respectively.

7.1.3.3.4 Manual tracking: The effect of repetition (attempt no.) on tracking

Total and final position errors showed similar distribution and similar mean errors and standard deviations (Figure 7-8) across all tracking attempts. Tracking was always behind the target though the participant hadn't started to before ~700 ms. When tracking the bowling ball, tracking errors did not change consistently with practice. For example, errors consistently decreased with practice when tracking the basketball but consistently increased when tracking the beach ball.

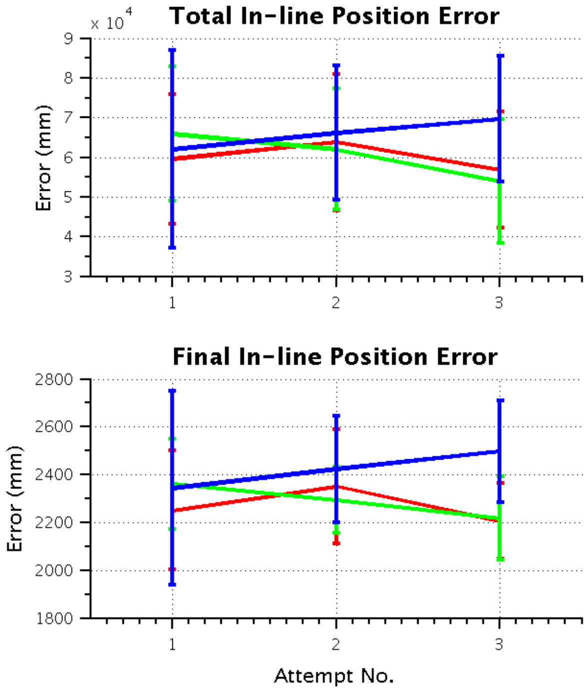


Figure 7-8. Manual tracking mean total and final position errors (with SD) along the line of target motion for the effect of repetition (attempt). Tracking of the bowling ball, basketball and beach ball are show in red, green and blue respectively.

7.1.3.4 Laser tracking

7.1.3.4.1 Laser tracking: Trajectory plots

As seen in time-series plots (Figure 7-5), tracking failed to keep up with the movement of the unseen target. Much like manual tracking data, the tracked location in the laser condition over 1500 ms (Figure 7-9) fails to cover the distance travelled by the unseen target in 730 ms apart from the second attempt when tracking 90° to the right. The distance tracked varied by condition angle but was not consistent between tracking attempts.

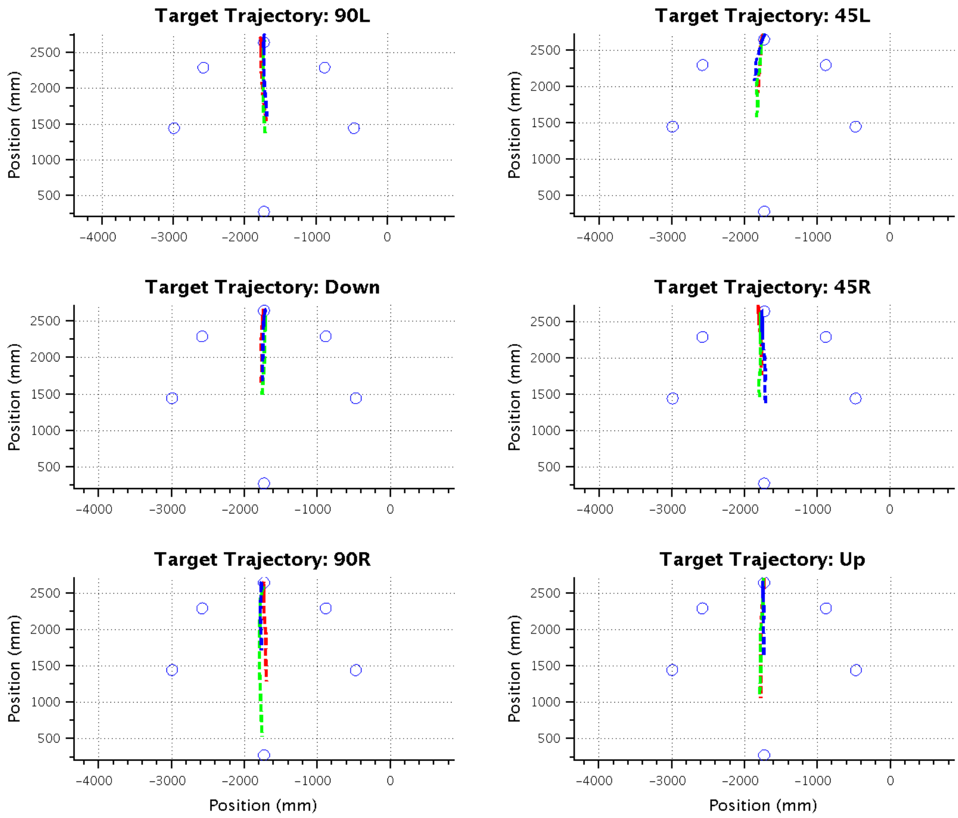


Figure 7-9. Trajectory plots of laser tracking of each ball in each angle condition. Mean tracked position of three attempts for bowling ball, basketball and beach ball are shown in red, green and blue (respectively). Solid lines show the first 730 ms of tracking and dashed lines show tracking from 730 to 1500 ms. Target start positions and radius are shown as blue circles. All trajectories are rotated to a common start position.

7.1.3.4.2 Laser tracking: Time series of tracked position error for individual target directions

The time-series of vertical position error from 1 to 730 ms show a smoothly increasing error from ~ 0 mm error to approximately 2500 mm error. These plots are featureless and not shown.

For horizontal position, the error at 1 ms is similar to that at 730 ms with no features in between. These plots are not show.

The commentary for the manual tracking time-series (Results 7.1.3.3.2) applies here also – that tracking error is error reflects target motion away from the start position.

7.1.3.4.3 Laser tracking: The effect of target angle on tracking

In the laser tracking condition, total and final position errors show that tracking in any direction was behind the target for all target types (Figure 7-10). As found when manual tracking, the total and final errors have similar profiles and the standard deviation of errors for each target angles appears not to be related to condition angle.

Mean tracking errors for the bowling ball (red lines) and beach ball (blue lines) conditions are similar but greater than those in the basketball condition. The clearest pattern of errors is in the basketball condition. Here, the errors are lowest when tracking a vertically descending target and increase as the angular deviation of each condition increases away from vertically down (±45º, ±90º and +180º).

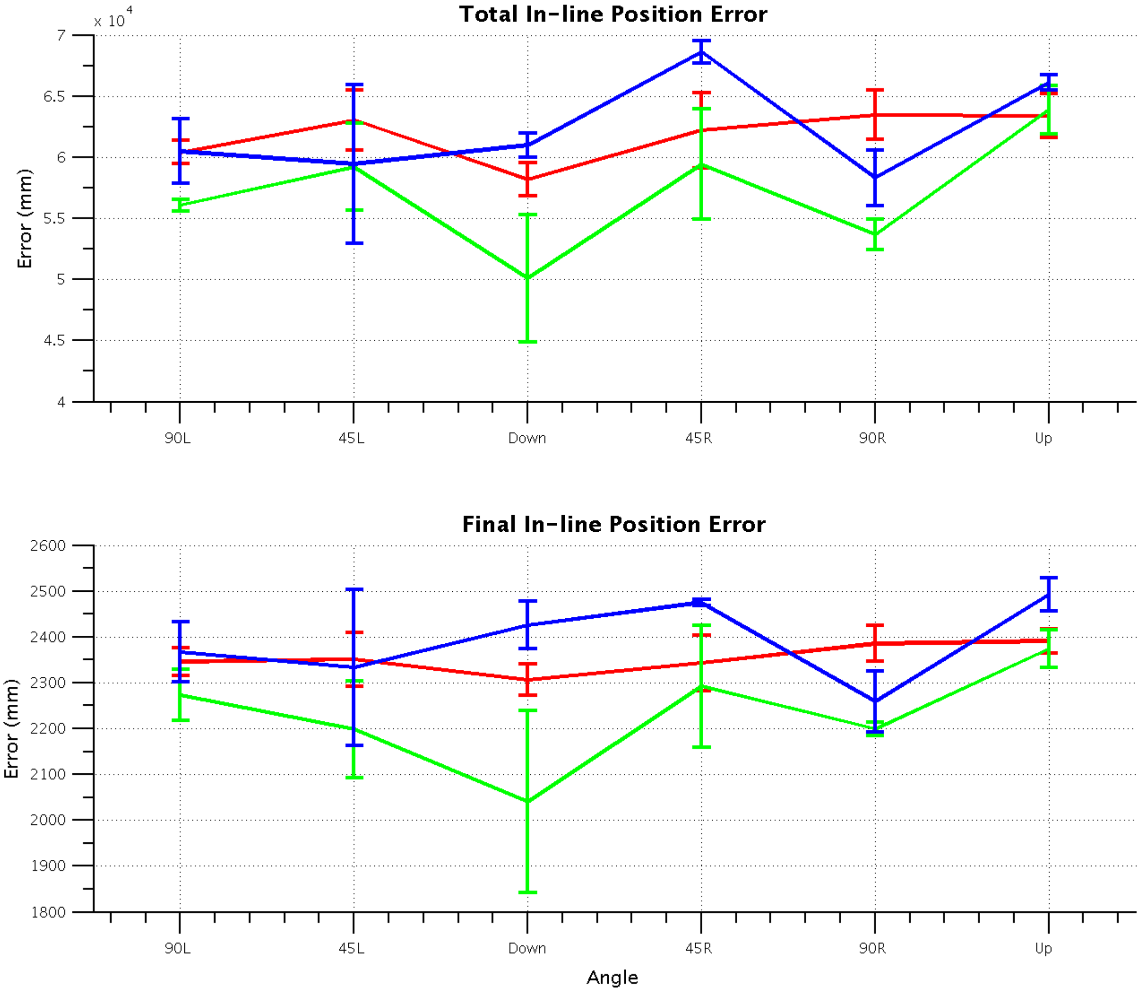


Figure 7-10. Laser tracking mean total and final position errors (with SD) along the line of target motion for different directions (angles). Tracking of the bowling ball, basketball and beach ball are show in red, green and blue respectively.

7.1.3.4.4 Laser tracking: The effect of repetition (attempt no.) on tracking

Total and final position error showed similar distribution and similar relative mean errors and standard deviations (Figure 7-11). Tracking was always behind the target. Mean tracking errors reduced with practice at each attempt and by similar amounts from first to third attempt for each type of target tracked.

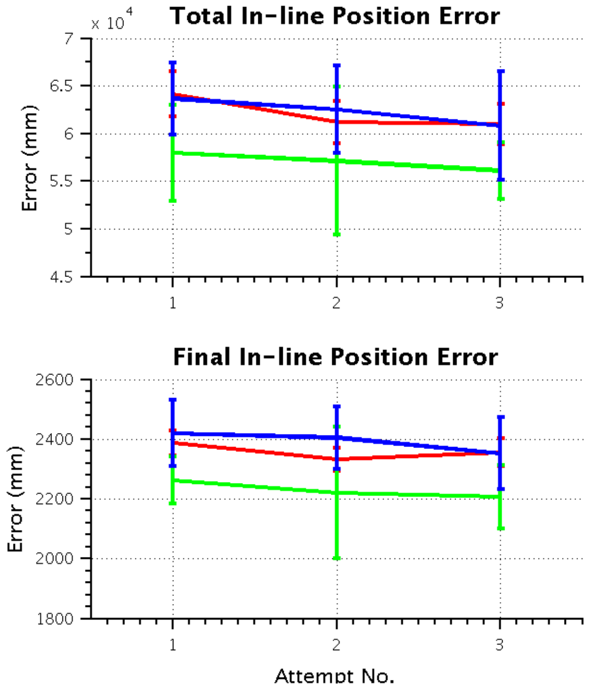


Figure 7-11. Laser tracking mean total and final position errors (with SD) along the line of target motion for the effect of repetition (attempt). Tracking of the bowling ball, basketball and beach ball are show in red, green and blue respectively.

7.1.4 Discussion

7.1.4.1 General findings

In the following discussions I present evidence that any internal model of gravity cannot be accessed when using imagination of gravitational movement alone. The main findings are:

- From the go-signal there was a delay of ~700 ms before tracking movement began. The delay was found when tracking at every angle in both the laser and manual conditions.

- This delay caused position, velocity and acceleration errors to increase rapidly for the 730 ms tracking period, due almost entirely to computed target movement.

- Once begun, tracking was very poor and much slower than tracking of visible targets, see Chapter 2 of this thesis – even over 1500 ms tracking did not cover the distance ‘travelled’ by the imagined target in 730 ms.

7.1.4.2 Manual tracking

When manual tracking, the indicated start position on the screen was offset from the target, though the offset depended on the position of the target. This is clearest in the trajectory plots of mean manual tracking for each target type (Figure 7-6). This offset was not found when laser tracking (Figure 7-9) indicating that, in that case, the calculated position of targets on the screen plane, methods of calculating screen intercept of the pointing vector, and rotation of tracking traces to zero were all correct. The participant whose data is analysed in this chapter also took part in the studies described in Chapters 2 and 3 but in those chapters they showed no such offset and, in general, manual tracking was accurate. Therefore there must be either an actual difference in the actual tracking by the same individual between those studies and the one described here, or some technical issue producing an apparent (not real) difference. For example, the position of Vicon markers defining the index finger tip or the position of the eyes may have been poor in the current experiment, or the instructions for manual tracking may have been more prescriptive causing an 'unnatural' form of tracking. The author cannot say with certainty where such a difference could lie. However since the error is visible when tracking the target's start location (Figure 7-6) and tracking at this point was stationary, it is likely that the offset is a result of technical error.

What is also clear from the trajectory plots is that manual tracking in the absence of a visible target covers only a fraction of the distance that the target would travel if under the influence of gravity. This was true for all directions and did not depend on the direction of imagined target movement (Figure 7-6 & Figure 7-7). In fact the tracking did not cover the distance in 1500 ms that the target would have covered in only 730 ms. This can be partially explained by late onset of tracking (around 700 ms after the 'go-signal' was given) but in the subsequent 800 ms it should have been possible to track the distance required since tracking of the same distance in the correct time of 730 ms was found for a visible target (Chapters 2 and 3). This shows that the participant greatly misjudged the effect that gravity has on free-falling objects when they cannot be seen. Further it indicates that the internal model of gravity identified by manual tracking in this thesis can only be accessed or elicited by a seen moving target and not by imagining target movement due to gravity.

Poor estimation of the effect of gravity was not confined to particular directions such as vertically upwards as might be expected from Chapter 2. Rather it was the case for all angles tested and equally so. Total and final mean position errors (Figure 7-7) suggest otherwise but the tracking offset identified in the trajectory plots (Figure 7-6) require I consider the in-line position error at the time of the 'go-signal' (Figure 7-12 below). The same pattern found in the total and final errors is seen in the starting errors meaning that actual tracking errors were likely to be equal for each angle tested.

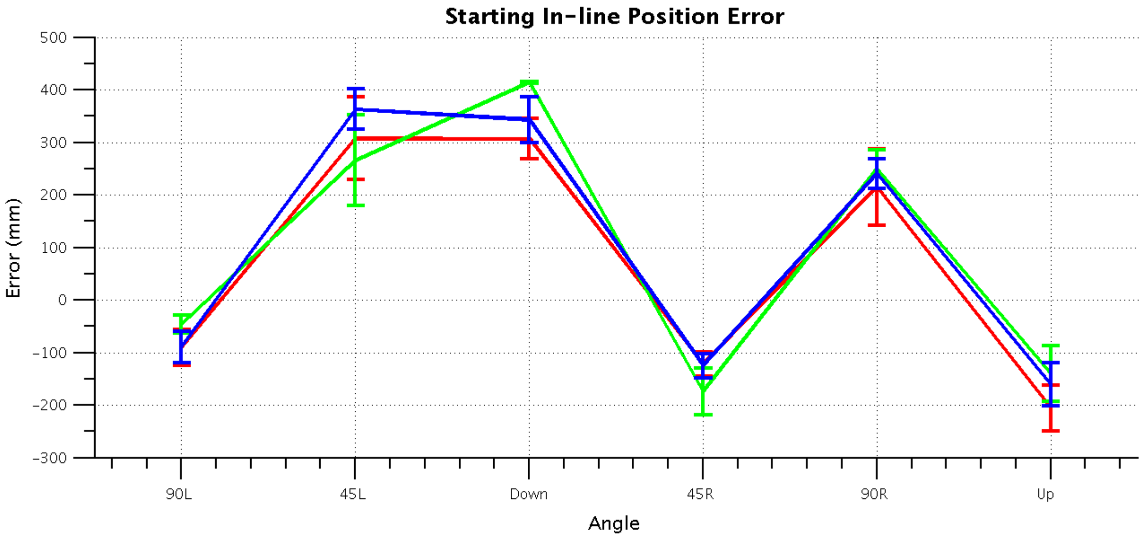


Figure 7-12. Manual tracking mean starting position errors (with SD) along the line of target motion for different directions (angles). Tracking of the bowling ball, basketball and beach ball are show in red, green and blue respectively

The total and final mean position errors are still informative. The lowest errors for each angle are, typically, when tracking of the bowling ball though the difference between mean errors at each angle is small and the standard deviation of errors is relatively large. The small sample size (n=3 per ball, per angle) is likely to cause this.

The distribution of errors in the attempt plots (Figure 7-8) is also likely to be caused by the small sample size (n=6 per ball, per attempt). The position errors show no overall change for the bowling ball, decreasing errors for the basketball and increasing error for the beach ball. It is possible that this distribution is meaningful and related to participant expectations about ball kinematics though a larger sample size is needed to ascertain this.

7.1.4.3 Laser tracking

Tracking was centered on the target for all angles at the start of the analysed time period unlike that found when manual tracking. However, like tracking in the manual condition, tracking in the laser condition failed to keep up with the target and didn't cover the distance in 1500 ms that the target would in 730 ms (Figure 7-9).

The error over 1500 ms appears to depend on the angle condition but the errors were not consistent between the attempts at each angle (Figure 7-9). For example, the second attempt when tracking 90° rightwards is the greatest distance tracked over 1500 ms but distance tracked over this period at the first and third attempts is typical of the distances tracked at other angles. When tracking upwards. The first and second attempts are unusually long but the third attempt is typical and when tracking 45° to the left the first and third attempt are unusually short. These inconsistencies likely result from only a single trial being available for each attempt at each angle. If more data were available from a number of participants it is likely that any pattern of errors might well disappear. Within the analysed time period (1 to 730 ms), tracking was consistent between and within angles (Figure 7-10 & Figure 7-11). However, there may be some interaction effect of target direction and ball type as lowest mean error in the laser condition is seen when tracking the basketball vertically downwards (Figure 7-10). The standard deviation of this error is relatively large so it is possible that the finding would disappear were more data available but if not then there would be evidence for an internal model influencing tracking of a target without any visible movement.

The mean time-series plots (Figure 7-5) presented at the start of the results section of this chapter are representative of tracking at every angle in the laser condition – tracking at all angles show similar featureless profiles from 1 to 730 ms. The time-series show that much of the tracking error is due to late starting of tracking - tracking started at ~700 ms for each angle. Late tracking onset is likely to have caused the large total and final errors but it does not account for the very poor tracking seen once he pointing arm began to move through to the end of period shown in the trajectory plots (Figure 7-9 dashed lines show tracking from 730 ms to 1500 ms). I have shown in previous chapters of this thesis that it is certainly possible to track the required distance in only 730 ms so such an accomplishment should be possible in 770 ms if an internal model of gravity were guiding movement. I therefore consider that such a model is not guiding laser tracking of the imagined target.

The time-series also show that tracking onset was slightly earlier with successive attempts, though by only ~20 ms. Though this may indicate that tracking was 'improving' (perhaps simply by reduction in movement initiation time), it should be noted that the standard deviation for the third attempt in this time-series is large compared to those for the first and second attempts. It is, therefore, more likely that this result is an artifact of low sample numbers and not meaningful.

One would expect the lowest errors (errors lagging least far behind the target) when tracking the bowling ball given heuristic beliefs of free-fall kinematics (Hubbard, 1997). However, low sample numbers may be the cause of the apparent better tracking of the basketball than either the beach ball or bowling ball (see mean errors). For these data at each ball at each angle there are only 3 data points available. Another reason might be the late onset of tracking which could mask any real tracking effort.

7.1.4.4 Ball type & effect of repetition

It is not clear whether the type of target 'tracked' has any influence on tracking behaviour because so little quality data was available from this study. There were only 3 data points for each angle tracked resulting in differences of means and standard deviations between angles that are potentially not meaningful because they would ordinarily fall within a large distribution of errors. Hubbard (1997) found that the greater the implied mass of a moving target, the greater the downward displacement when reporting the final position of the target after it suddenly disappears. This indicates that some internal representation of the mass of seen objects exists, and suggests that I would find faster tracking of more massive objects than less massive objects (e.g. bowling ball versus beach ball) if more data were available from this study.

The effect of repetition was not clear in the data presented again because of low sample numbers. I hypothesise that there should be no overall change in tracking errors from the first attempt to the final attempt in any given condition because there is nothing to compare actual performance to as there was in Chapters 2 and 3 where I found modification of tracking with practice.

7.1.4.5 Main conclusions

Tracking was poor in both the manual and laser tracking conditions and did not depend on the direction of imagined motion. Total and final errors were not informative of the nature of tracking due to extremely late initiation of tracking identified in time-series plots – initiation was ~700 ms into the 730 ms tracking time period. However, time-series and trajectory plots over 1500 ms show that tracking was still not able to cover the distance required in 730 ms i.e. tracking was not sufficient even if considering 770 ms after movement initiation. This contrasts with the results of Chapters 2 and 3 of this thesis where tracking was typically able to cover the required tracking distance in 730 ms, suggesting that the participant in this experiment was not able to access and use their internal model of gravity that I have argued results in the pattern of errors found in other chapters of this thesis when tracking a visible target. I therefore suggest that there has to be a visible target for internal model 'assistance' of tracking.

7.1.5 Limitations & further work

The identification of markers and the frequent appearance of 'ghost' markers (reflections picked up not from actual markers and occasionally signal error) resulted from conditions that were sub-optimal due to:

- Only 7 Vicon cameras being available for this experiment (10 cameras were used in Chapters 2 and 3).

- Cameras positioned far away from participants. Cameras could only be mounted to a rail on the wall of the laboratory rather than onto closer portable tripods used in other experiments.

- Higher ambient light levels (compared to the laboratory used in Chapters 2, 3, 4 and 5) due to lack of light proofing.

- Infra red light pollution from lights outside of the laboratory.

This ambient light also reduced the brightness, contrast and sharpness of images projected onto the screen thus considerably reducing their realism. The consequence of this is that only one participant was found to have good enough quality data for the entire set for the laser and manual tracking conditions. It may be possible to extract the gaze vectors for this participant but I expect a high chance of poor quality data because of the use of an analogue to digital box during testing that I later found to be faulty (see Appendix 7.3.1.2).

The main limitation in analysing the output of this study was the number of data points available. This of course is due to only a single subject entering the data set despite 21 subjects participating in the experiment. Appendix 7.3 details some of the technical difficulties encountered during this experiment that resulted in the exclusion of 20 participants. Further work on the data set collected could either focus on attempting to recover more data either by examining other subjects, or attempt to analyse the eye movement data from the subject presented here. However, the participant analysed was deemed to have the highest quality data of all participants tested yet still uncertainty on the calculated manual tracking position, the tracking start delay in manual and laser tracking, and the high level of noise in eye movement signal (Appendix 7.3.1.1) indicate that the available data still had problems. It therefore is perhaps most prudent to repeat the experiment under more favourable conditions than were available at the testing originally.

Participants reported the handheld laser unit used by participants (see Methods 7.1.2.3) to be cumbersome because of its width. In the subsequent experiments described in Chapters 2 and 3 a slimmer and lighter model was used. No difficulties were reported with this unit so any further work involving tracking with a handheld laser should similar unit. Another development from this study to the others in this thesis is regarding the stimuli – stimuli in those experiments were rendered with frontal illumination to avoid directional 'clues' in the stimulus. For example, illumination from the top is typical because of natural and unnatural lighting where as it is less common to see lighting from underneath. It is not known whether such an implied verticality to stimuli in an otherwise blank scene could affect tracking output but further should consider using frontal illumination.

7.2 References

Hubbard, T. L. (1997). Target size and displacement along the axis of implied gravitational attraction: Effects of implied weight and evidence of representational gravity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *23*(6), 1484–1493.

Kim, I. K., & Spelke, E. S. (1992). Infants' Sensitivity to Effects of Gravity on Visible Object Motion. *Journal of Experimental Psychology: Human Perception and Performance*, *18*(2), 385–393.

Le Séac'h, A. B., Senot, P., & McIntyre, J. (2010). Egocentric and allocentric reference frames for catching a falling object. *Experimental Brain Research*, *201*(4), 653–62.

McIntyre, J., Zago, M., Berthoz, A., & Lacquaniti, F. (2001). Does the brain model Newton's laws? *Nature Neuroscience*, *4*(7), 693–4.

Senot, P., Zago, M., Lacquaniti, F., & McIntyre, J. (2005). Anticipating the effects of gravity when intercepting moving objects: differentiating up and down based on nonvisual cues. *Journal of Neurophysiology*, *94*(6), 4471–80.

Senot, P., Zago, M., Le Séac'h, A., Zaoui, M., Berthoz, A., Lacquaniti, F., & McIntyre, J. (2012). When up is down in 0g: how gravity sensing affects the timing of interceptive actions. *Journal of Neuroscience*, *32*(6), 1969–73.

Twardy, C. R., & Bingham, G. P. (2002). Causation, causal perception, and conservation laws. *Perception & Psychophysics*, *64*(6), 956–68.

Zago, M., Iosa, M., Maffei, V., & Lacquaniti, F. (2010). Extrapolation of vertical target motion through a brief visual occlusion. *Experimental Brain Research*, *201*(3), 365–84.

7.3 Technical details

7.3.1 Technical limitations

7.3.1.1 Iris colour

We discovered that very pale and patterned irises were unsuitable for eye tracking because the ASL system could not reliably distinguish the corneal reflection from the already pale iris background. Only one participant was lost due to this limitation.

Removing the shift and gain interface

For the first 5 participants tested in the preliminary study (see Chapter 1.6), data was transferred from the ASL Model 6000 control unit to the Vicon MX Ultranet's analogue to digital box via a shift and gain interface box that was later found to be faulty. The voltages (horizontal and vertical eye-in-orbit position) recorded varied by circa 0.1 V as the eye tracked around the points of the calibration grid. When combined with laboratory electronic noise this small signal variance resulted in a poor signal to noise ratio (Figure 7-13). The shift and gain interface was removed and signals fed directly from the ASL controller to the Vicon MX Ultranet's analogue to digital box via a custom built adapter (supplied by Des Richards). The recorded voltage variance increased to circa 5v, and consequently noise levels were comparatively reduced, yielding an excellent signal to noise ratio thereafter (Figure 7-13). Eye movement data from affected data is analysable following pre-treatment of signals with a low cut 30 Hz filter to remove the high frequency noise (Figure 7-14).

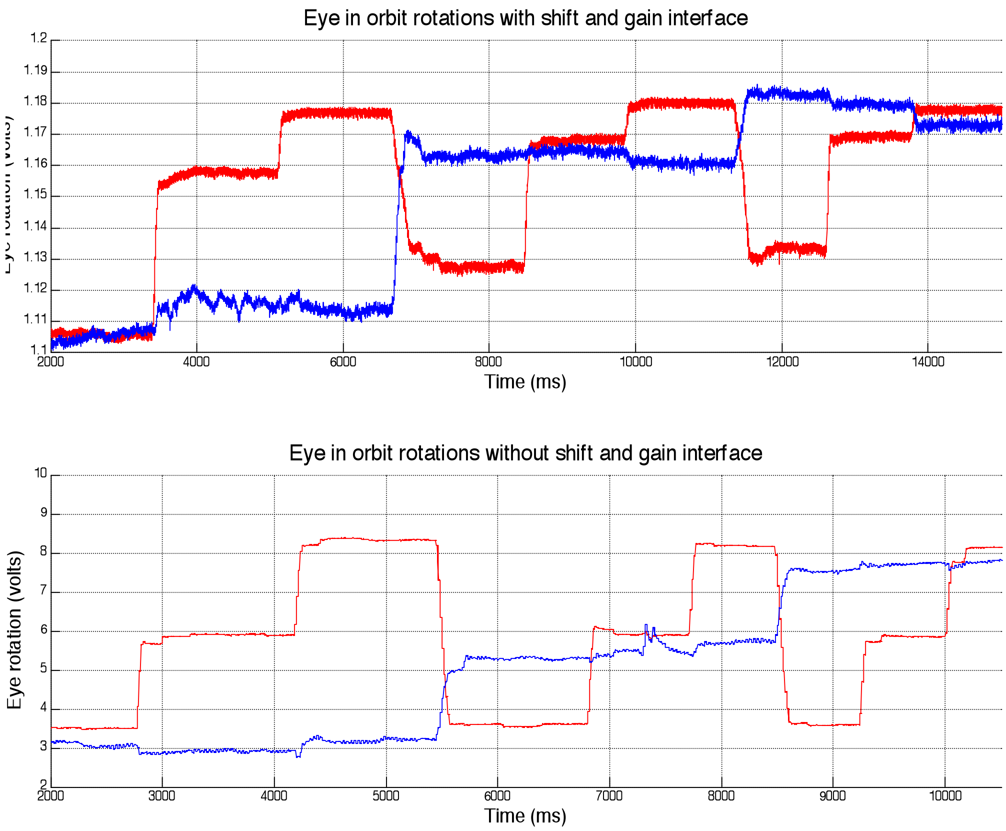


Figure 7-13. Calibration trials before and after the removal of the switch and gain interface box. Before the SGI was removed the recorded variance of the analogue signal output was limited to ~1v whereas direct output from the ASL controller to the Vicon MX Ultranet (via an analogue to digital box) recorded a variance of analogue signal output of ~5v. Signal to noise ratio is greatly reduced after removal of the box.

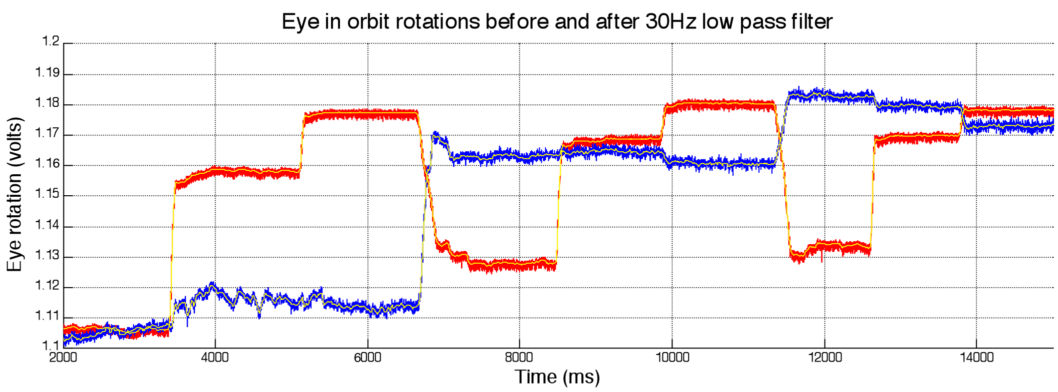


Figure 7-14. Raw eye in orbit rotation (x (red) and y (blue) signals and the same signals after a 30Hz low cut filter (yellow). Noise from the switch and gain box masked true analogue signals but filtering makes signals useable.

7.3.1.2 Equipment failure and scheduling difficulties

The computer running the interface with the ASL eye tracker failed irreparably during testing in early December 2009. A compatible machine was obtained and substituted, and new eye tracker control software sent from the US. Testing resumed in late January 2010 though the laboratory was lost because other IRM researchers had booked the space. After regaining use of the laboratory only 15 working days were left before the lab had to be packed down for moving to the new laboratory. Experiments could not be conducted at the weekend because the dark conditions required conflicted with MMU's early weekend closures. X-Ray maintenance in an adjacent room and equipment moving removed two days leaving only 13 testing sessions to finish Experiment 1. On top of these difficulties, it was disheartening to discover that during the transfer of equipment and use of the lab by other IRM researchers the projection screen used in this experimental programme was torn in its centre.

7.3.1.3 Construction of a new laboratory

At the start of my MPhil study it was expected that a new purpose-built lightproof laboratory would be available in April 2009. Construction delays, however, meant that I was unable to move into the new building until April 2010. Before my arrival and during my first months we (the author, Professor Marple-Horvat and Professor Loram) factored lightproof conditions into experimental design and equipment selection. Although an interim laboratory was available it could not be made lightproof. The insurmountable problem was that with high levels of ambient illumination, the large projected images of visual targets were too faint by contrast to appear as realistic objects. The start of experiments was consequently delayed by 6 months to late autumn 2009 when nights were darker earlier, so that participants were not required to come in very late, and experiments could be completed before University closing time (Monday-Thursday - 9pm, Friday - 8pm, Saturday and Sunday - 4pm).

The new Motor Control Laboratory in which experiments were to continue was completed in April 2010 though the space was unusable for our experiments because ceiling fixtures were installed to low to accommodate our apparatus. This prevented the vital projection screen from being erected. The experiments described in this thesis could therefore not begin until this was rectified in December 2010 (9 months after the laboratory was built).

7.3.1.4 Consequences of technical delays

The difficulties outlined above resulted in a delay of at least 14 months to the planned experimental studies at the start of the research programme.

7.3.2 Target stimulus

7.3.2.1 Stimulus presentation timings

A signal pulse was used to begin a stimulus presentation. This signal was recorded in time along with eye in orbit rotation and marker positions using the Vicon system. However the time of stimulus presentation may have been delayed due to signal transmission, activation of stimulus playback by software and projector response time. Without knowing the total delay it may appear that participants being to track a target before it is presented, and if the delay is not consistent then it would prove impossible to judge participant tracking performance. A button activated signal pulse was sent simultaneously to a stimuli-generating computer to trigger stimuli and to the Vicon system to be recorded.

7.3.2.2 What is the playback delay?

To investigate playback delay the experimental apparatus was assembled as for the main experiments though a signal splitter was placed at the root of the signal pulse to provide input to an oscilloscope. A 25Hz digital video camera (Canon FS100) recorded the Vicon Nexus monitor, the oscilloscope and the projected image (Figure 7-15). A selection of stimuli videos were run (including vertically up, vertically down and 5° left and right) and all latencies were the same.

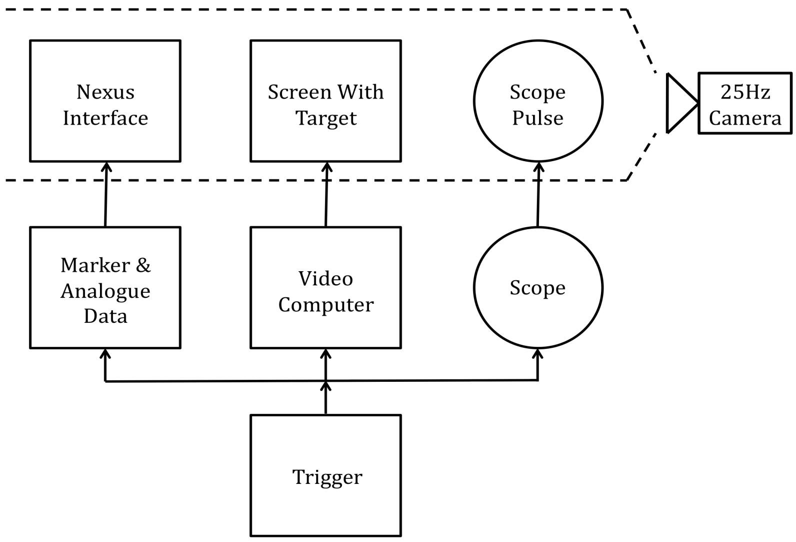


Figure 7-15. Schematic of the apparatus.

Time zero was starting the digital video camera, and then starting the experimental recording and stimulus presentation as described in the main experiments. Events of interest were:

1. Time of pulse appearance on the oscilloscope (OP).

2. Time of pulse appearance on the Vicon Nexus monitors (NP).
3. Time of target appearance on the screen (TA).

The time from the start of each trial's video to an event and the events' time relationship to each other are shown in Table 7-1.

Table 7-1. Appearance times of signals on oscilloscope and Vicon Nexus monitors and appearance times of the first target for 30 trials. Time is measured relative to the start of video recording. Time differences between oscilloscope and Vicon Nexus monitors to the appearance of the stimulus remained consistent and indicate a playback delay of 564ms.

Trial	Oscilloscope Pulse (OP) (ms)	Nexus Pulse (NP) (ms)	Target Appearance (TA) (ms)	TA-OP	TA-NP	(TA-OP) – (TA-NP)
1	2360	2440	4920	2560	2480	80
2	2440	2520	5000	2560	2480	80
3	2720	2800	5280	2560	2480	80
4	2400	2480	4960	2560	2480	80
5	3120	3200	5680	2560	2480	80
6	2240	2320	4800	2560	2480	80
7	3000	3080	5600	2600	2520	80
8	2400	2480	4920	2520	2440	80
9	2560	2640	5120	2560	2480	80
10	3120	3200	5680	2560	2480	80
11	2360	2440	4920	2560	2480	80
12	1640	1720	4200	2560	2480	80
13	1720	1800	4280	2560	2480	80
14	2600	2680	5120	2520	2440	80
15	1920	2000	4480	2560	2480	80
16	2240	2320	4800	2560	2480	80
17	2200	2280	4760	2560	2480	80
18	2040	2120	4600	2560	2480	80
19	2360	2440	4920	2560	2480	80
20	2480	2560	5040	2560	2480	80
21	2600	2680	5200	2600	2520	80
22	2840	2920	5440	2600	2520	80
23	2240	2320	4760	2520	2440	80
24	2160	2240	4720	2560	2480	80
25	2920	3000	5480	2560	2480	80
26	3120	3200	5720	2600	2520	80
27	2360	2440	4920	2560	2480	80
28	2080	2160	4680	2600	2520	80
29	3000	3080	5560	2560	2480	80
30	2320	2400	4920	2600	2520	80
Mean				2564	2484	80
SD				21.9089	21.9089	0
SEM				4	4	0

The differences between OP to TA and NP to TA are consistent (mean=80, SD=0, SEM=0which means that there is a non-variable transmission and reception time from the button press to the Vicon system. The standard deviations and standard error means for TA-OP and TA-NP are the same (mean=2564. SD= 21.9089, SEM=4 and mean=2484. SD= 21.9089, SEM=4) which means that the internal processing and display time by Vicon is consistent.

The oscilloscope should yield the most accurate time of the signal pulse because there is less processing involved before display feedback and because there is little variability in timings I can take the mean TA-OP (2564ms) as the true delay between signal change and first target appearance. Two seconds of blank image preceded the target in the video meaning that total processing delay from trigger press to the video play on the screen was 564ms.

7.3.2.3 Are stimuli presented at the correct speed?

Video stimuli were produced at 60fps in accordance with the optimal frame rate of the Canon XEED SX7. It could be that the delay of from trigger press to video playback of 564 is partly due to incorrect frame presentation speed in the final image.

To investigate the playback speed of the stimuli the image generating apparatus was assembled and operated using the same methods as the main experiments though before each trial a 25Hz digital video camera (Canon FS100) was set to record the screen onto which the stimuli were projected (see Figure 7-16). Prior to target movement the target was red for 1s before turning to amber for 1s then turning to green at movement start (Figure 7-17). Appearance times of each coloured target relative to the start of the trial are shown in

Table 7-2.

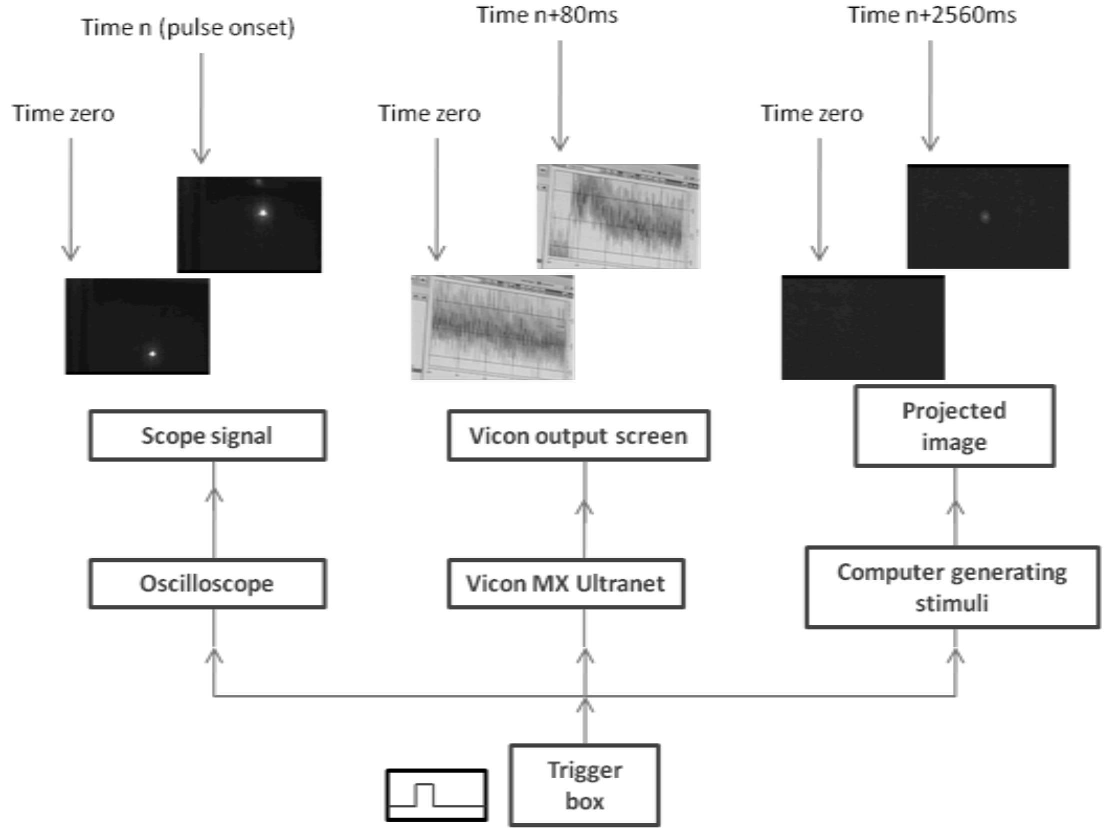


Figure 7-16. Schematic representation of the experimental set-up to determine the delay between the trigger pulse (seen on an oscilloscope (left) and on via the Vicon (centre)) and the appearance of the target.

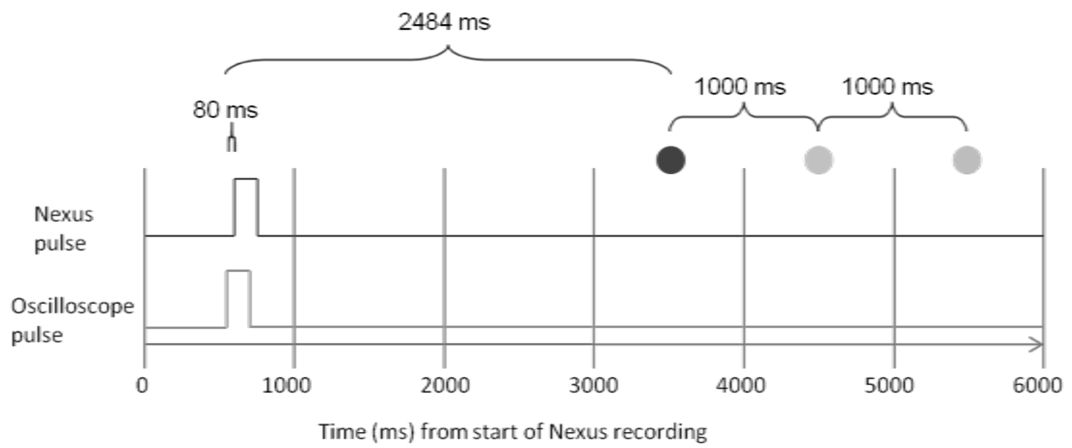


Figure 7-17. An example of the timing of stimulus events following triggering of data acquisition.

Table 7-2. Appearance times of target colours relative to start of digital video recording for 20 trials. Recorded stimulus was presented at the correct frames per second (60Hz).

Trial	Red Appearance (RA) (ms)	Amber Appearance (AA) (ms)	Green Appearance (GA) (ms)	AA-RA	GA-AA
1	8320	9320	10320	1000	1000
2	7280	8280	9280	1000	1000
3	6120	7120	8120	1000	1000
4	6800	7800	8800	1000	1000
5	5840	6840	7840	1000	1000
6	6000	7000	8000	1000	1000
7	5880	6880	7880	1000	1000
8	7400	8400	9400	1000	1000
9	6040	7040	8040	1000	1000
10	5400	6400	7400	1000	1000
11	10880	11880	12880	1000	1000
12	11560	12560	13560	1000	1000
13	10960	11960	12960	1000	1000
14	6040	7040	8000	1000	960
15	7720	8720	9720	1000	1000
16	6360	7360	8360	1000	1000
17	5360	6360	7360	1000	1000
18	5560	6560	7560	1000	1000
19	5840	6840	7840	1000	1000
20	7800	8800	9800	1000	1000
Mode				1000	1000
Mean				1000	998
SD				0	8.94
SEM				0	2

The above shows a consistent time delay of 1000ms between changes in target colour, which is consistent with the intended production on the stimulus at 60Hz. The lower GA-AA at Trial 14 (960 ms) likely results from the difference in video capture rate (25Hz) to stimulus presentation (60Hz) i.e. 1000 ms / capture rate = 1000/25 = 40.

7.3.3 Eye tracking

7.3.3.1 ASL501 calibration

Immediately prior to testing the ASL 501 eye tracker was calibrated as participants sat stationary and gazed at nine points arranged in a grid that was presented on the screen 3 m ahead of them (circles labelled 1-9 in Figure 7-18a). The eye tracker outputs two voltage signals corresponding to the x and y rotation of the eye in the orbit. Prior to analysis these were filtered using a 4th order 30 Hz Butterworth filter (Figure 7-18b&c). An angle from the centre row (vertical) and column (horizontal) was calculated to each calibration point from the eye (Figure 7-18d&e). The mean of the voltage outputs was taken for a time period (typically 1-2 s) gazing at each calibration point in turn and to these 9 points a first order polynomial was fitted to calculate coefficients used to convert voltage signals into eye in orbit rotation angles. The mean position of the left eye (the monitored eye), mean head pitch and mean head yaw were also calculated for the duration of this calibration.

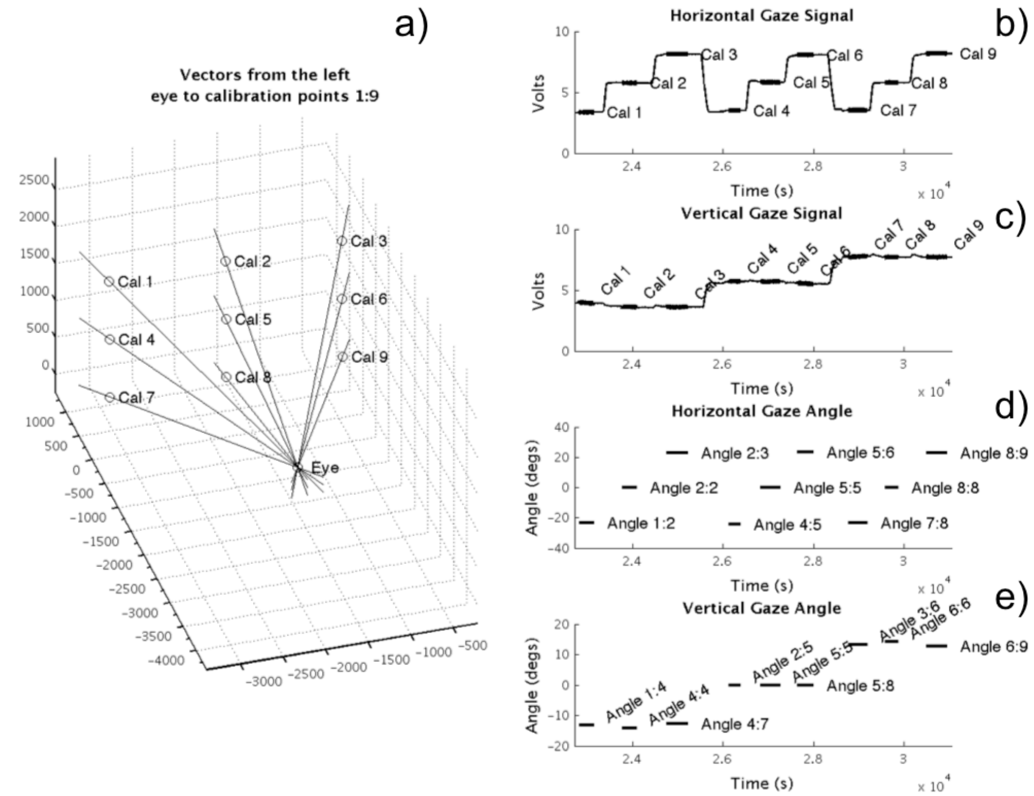


Figure 7-18. Horizontal/Vertical gaze volts with corresponding angles. Plots b and c show the time course of the horizontal and vertical gaze volts and plots c and d show gaze angles for those times as the participant looked at calibration points 1 to 9 (circles in plot a). The labels at the marks in plots d and e denote the calibration points of which the angle (via the eye) belongs to (e.g. in plot d the first label is 'Angle 1:2' which is the angle formed by calibration point 1 to the eye then to calibration point 4).

Head pitch (rotation in the sagittal plane) and yaw (rotation in the axial/horizontal plane) were calculated using the positions of the front left head marker, rear left head marker and a virtual marker made up of different components of each of these depending on whether pitch or yaw was the aim. The pitch virtual marker was made up of the *x* and *y* of the front left head marker and the *z* of the rear left head marker, whilst the yaw virtual head marker was made up of the *x* of the rear left head marker and the *y* and *z* of the front left head marker (Figure 7-19a&b). For pitch the angle from the pitch virtual marker to the rear left head marker to the front left head marker was taken (Figure 7-19a) and for yaw the angle from the front left head marker to the rear left head marker to the yaw virtual marker was taken (Figure 7-19b) and the mean of each taken from the sample time (Figure 7-19c&d). The system was recalibrated if the headset moved independently of the head (rotational slip) or if a calibrated component of the headset was disturbed.

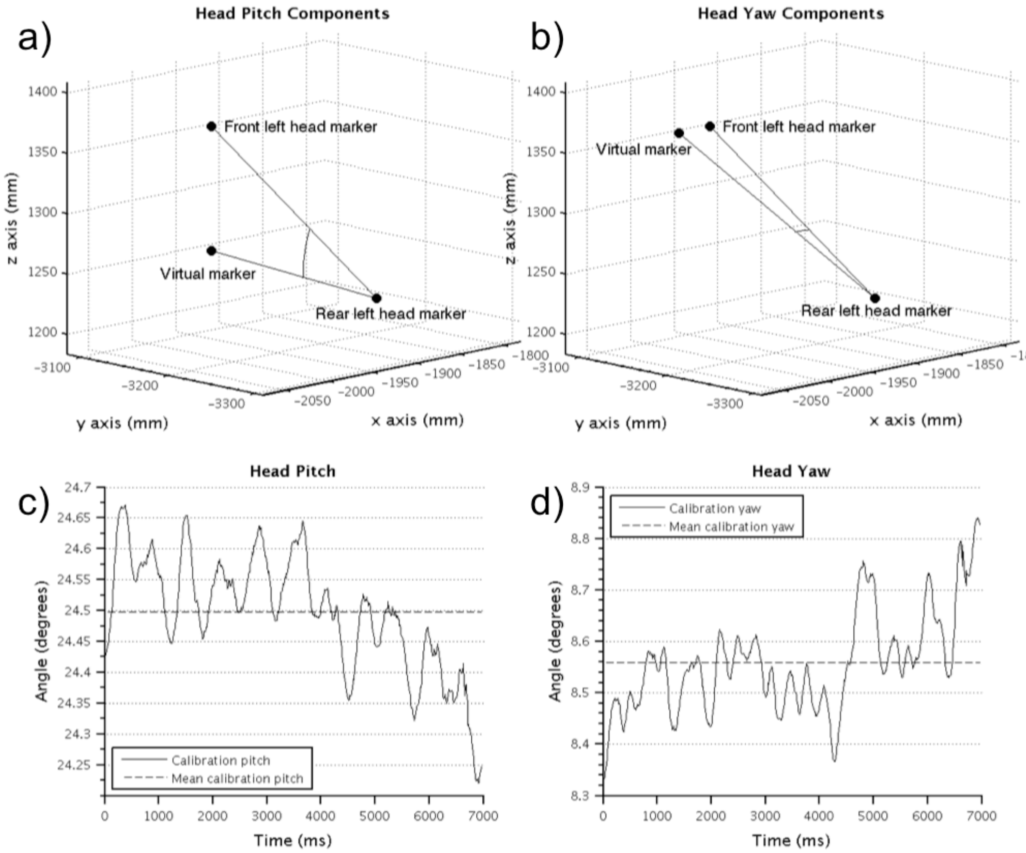


Figure 7-19. Components required for calculation of head pitch and yaw with example measurements. Plots a&b: Real and virtual markers used to calculate head pitch and yaw. Plots c&d: an example of head pitch and yaw during the calibration period with an overlay of mean pitch and yaw values.

7.3.3.2 Experimental trials

ASL sampling of the x and y eye in orbit rotation was at 60 Hz and recorded by the Vicon system at 1000 Hz so, to match the 100 Hz marker sampling, the eye in orbit rotations were down sampled to 100 Hz using linear interpolation, following application of a 4th order 30 Hz Butterworth filter. Eye in orbit rotation voltages were then converted into eye in orbit rotation angles using the calibration coefficients, and the pitch and yaw of the head were calculated in the same way as for the calibration except the angles and head rotations were calculated for every time point and not averaged.

7.3.3.3 Calibration gaze location

Calculation of 3D gaze intercept onto the screen plane was possible using trigonometry. In calibration trials the 3D gaze location was made up of a horizontal position (*HP*) and a vertical position (*VP*) that were calculated using Equation 7-1 and Equation 7-2.

Equation 7-1. Calculation for horizontal position of gaze in a calibration trial.

$$HP_t = (Cal6 - Cal5/d1) \times \left(D_t \times \tan\left(H\Theta_t\right)\right)$$

Equation 7-2. Calculation for vertical position of gaze in a calibration trial.

$$VP_t = (Cal2 - Cal5/d2) \times \left(D_t \times \tan\left(V\Theta_t\right)\right)$$

Where *Cal*2/5/6 are calibration points 2/5/6 defined in x, y, z (see Figure 7-18a), *d*1 is the distance from *Cal*5 to *Cal*6, *d*2 is the distance from *Cal*2 to *Cal*5, *D* is the distance from the eye to centre calibration point and *H*Θ/*V*Θ is the horizontal/vertical angle.

The gaze location (*GL*) at each moment in the calibration trial was calculated using Equation 7-3.

Equation 7-3. Calculation for complete position of gaze in a calibration trial at any time (t)..

$$GL_t = HP_t(x,y,z) + VP_t(x,y,z) + Cal5(x,y,z)$$

Over the period during which gaze was stably fixated on each calibration point, the mean error and SD of calculated gaze position relative to each points actual location was calculated (Figure 7-20). The mean and SD of these positions on the screen plane is show in Figure 7-21.

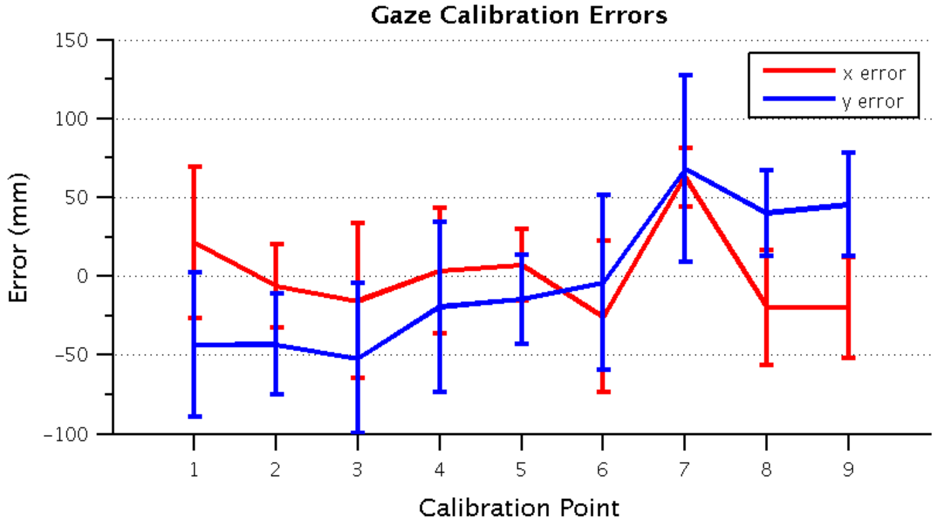


Figure 7-20. Mean error and SD of gaze position at each calibration point (calibration error) for all participants successfully calibrated participants.

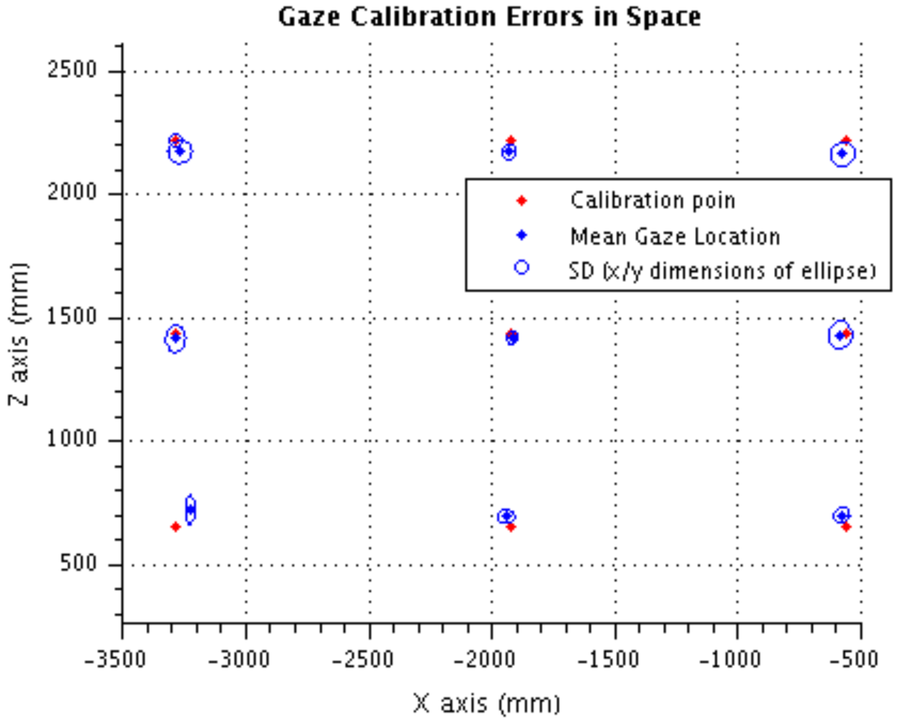


Figure 7-21. Mean and SD of gaze position at each calibration point for all successfully calibrated participants. Red spots are calibration points, blue spots are mean gaze positions and blue ovals represent the horizontal and vertical SD of gaze position around the mean.

7.3.3.4 Experimental gaze location

Eye in orbit rotations was summed with head rotation to yield gaze angles for a freely moving head, and the intercept of the gaze vector on the screen was calculated (Figure 7-22).

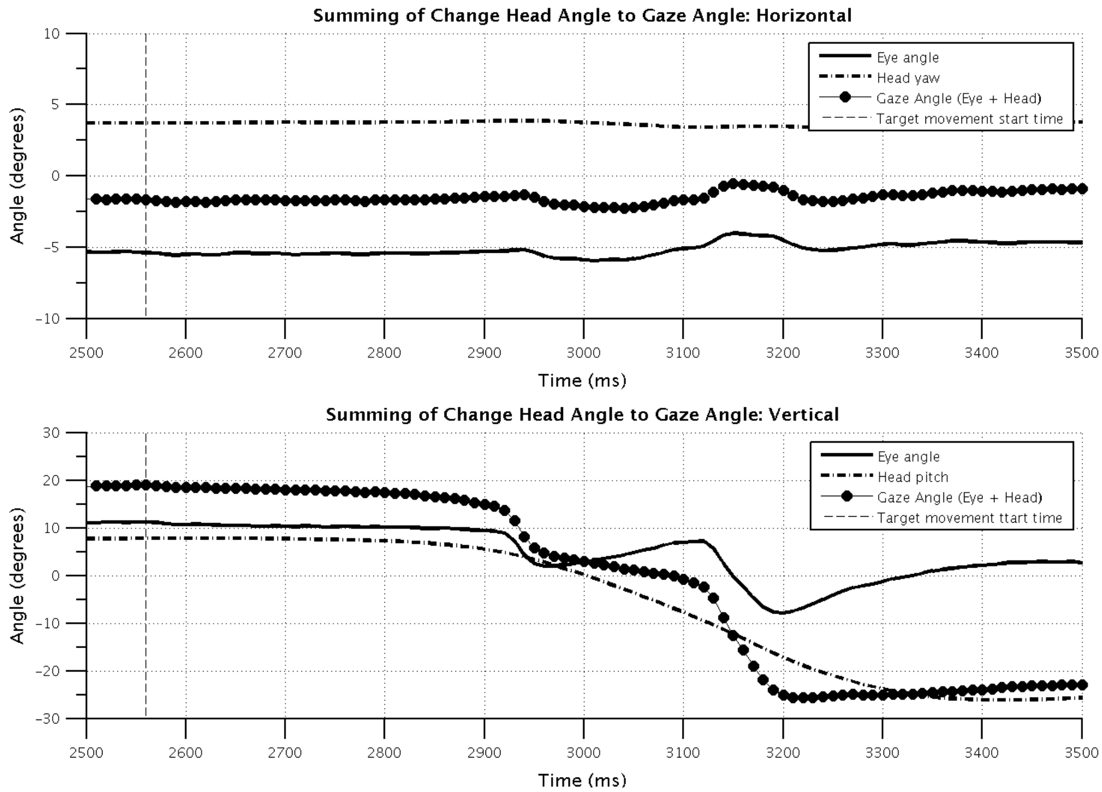


Figure 7-22. Addition of head rotation to eye in orbit rotation angles.

Horizontal position (*HP*) and vertical position (*VP*) at each moment (t) in experimental trials were calculated using Equation 7-4 and Equation 7-5.

Equation 7-4. Calculation for horizontal position of gaze in an experimental trial..

$$HP_t = (Cal6 - Cal5/d1) \times \left(D_t \times \tan\left(H\Theta Y_t\right)\right)$$

Equation 7-5. Calculation for vertical position of gaze in an experimental trial.

$$VP_t = (Cal2 - Cal5/d2) \times \left(D_t \times \tan\left(V\Theta P_t\right)\right)$$

Where *Cal*2/5/6 are calibration points 2/5/6 (defined in x, y, z), *d*1 is the distance from *Cal*5 to *Cal*6, *d*2 is the distance from *Cal*2 to *Cal*5, *D* is the distance from the eye to the screen plane, *HΘY* is the horizontal gaze angle plus change in head yaw and *VΘP* is the vertical gaze angle plus change in head pitch.

The gaze location (*GL*) in an experimental trial was calculated using Equation 7-6.

Equation 7-6. Calculation for complete position of gaze on the in an experimental trial.

$$GL_t = HP_t(x,y,z) + VP_t(x,y,z) + Cal5(x,y,z) + E_t$$

Where E is the difference from mean calibration eye position to instantaneous trial eye position.

To compensate for any possible change in screen plane location the intercept of a vector from the eye through the gaze location onto the screen plane was taken as the true gaze location.

7.4 Data exclusion rates and averaging details

In experiments 1 (varying direction of straight line target movement - Chapter 2) and 2 (varying amplitude of descending straight line target movement - Chapter 3) all subjects participated in all tracking method conditions but in each of these conditions only a selection of participants were analysed fully). The following process of elimination of poor data took place for experiments and 2:

1. First, all trials were checked so participants could be separated into two groups: a qualifying group ('Generally good') and an exclusion group ('Poor'). Exclusion was based on the individuals' data quality (namely signal drop outs) and was not influenced by ability to perform the task.
2. The second level (offset) split the previously qualifying participants into two qualifying groups ('No offset' and 'Consistent offset') and one exclusion group ('Inconsistent offset'). Those with no offset proceeded to the next stage immediately. The gaze tracking apparatus on the head sometimes slipped. Where the apparatus was loose an inconsistent gaze offset resulted in irrecoverable data and those participants were excluded. However in experiment 1 (Chapter 2) there were 5 participants for whom the headband appears to have slipped only once so the pattern of gaze for all angles looks correct (i.e. similar to those in 'No offset') though offset. For these participants, following calculation of gaze intercept on the screen but preceding rotation to zero, their intercepts were transposed by the difference of the mean starting positions to the target start position. I employed this method only when certain the participants' intercepts were consistently offset and the quality of the data was excellent. The gaze data sets would otherwise be impoverished by the low qualifying rate in level 1 ('Generally good').

3. At level 3, participants with complete data qualified to 'No. with no bad trials'. Those with incomplete data sets (sets with tracking attempts excluded typically due to signal drop out) moved to level 4.
4. At level 4 (participants with incomplete data sets) a conservative rule (a) was applied to reduce exclusion of incomplete data sets by the listwise analysis employed in the ANOVA tests. Where more than a single attempt at an angle was missing, that subjects moved to 'Failed rules' and were excluded (b). Where subjects qualified they moved to 'Meets Rules'. The frequency of filling gaps in data for each subject where the rule was applied is listed in the table below each figure in each tracking method condition.
5. The final selection of participants for each tracking method condition was made up of those in the groups 'Meets rules' and 'No. with no bad trials'.
    a. For subjects who had just a single attempt for an angle missing (e.g. 2nd attempt at 5°) that value was filled with the mean of all values for all other subjects for the same attempt at that angle (i.e. 2nd at 5°).
    b. Where subjects failed the conservative rule (a), they typically did so by failing it at two or three attempts at many angles. One subject with no offset failed the rules based on two failed attempts at a single angle for the gaze only tracking method. They were made available for inclusion by foregoing the exclusion criteria of the rule and applying the mean average part of the rule for both attempts in that angle.

A flow chart illustrating exclusion process and a table describing the number of corrections at level 4 is shown below for each tracking method condition for both experiments (manual - Figure 7-23 & Table 7-3; laser - Figure 7-24 & Table 7-4; gaze only - Figure 7-25 & Table 7-5; gaze in the manual condition - Figure 7-26 & Table 7-6; and gaze in the laser condition - Figure 7-27 & Table 7-7).

Manual Trials

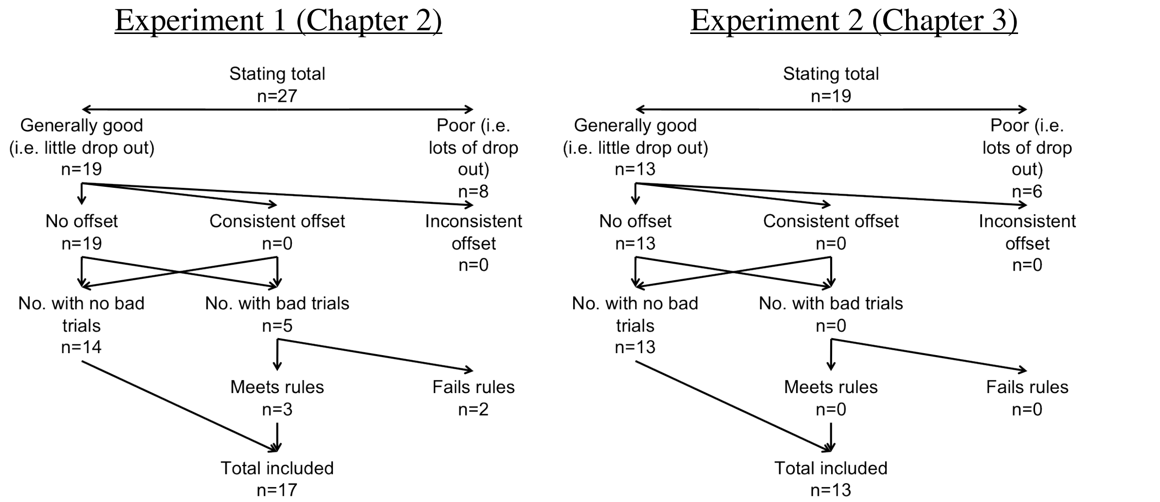


Figure 7-23. Flow chart of data exclusion for the manual condition in experiments 1 and 2.

Table 7-3. Description of any trials in which correction by a conservative rule was employed for the manual condition in experiments 1 and 2.

Participant no.	No. attempts corrected using rules	Participant no.	No. attempts corrected using rules
2	2	N/A	N/A
12	1		
19	1		

Laser Trials

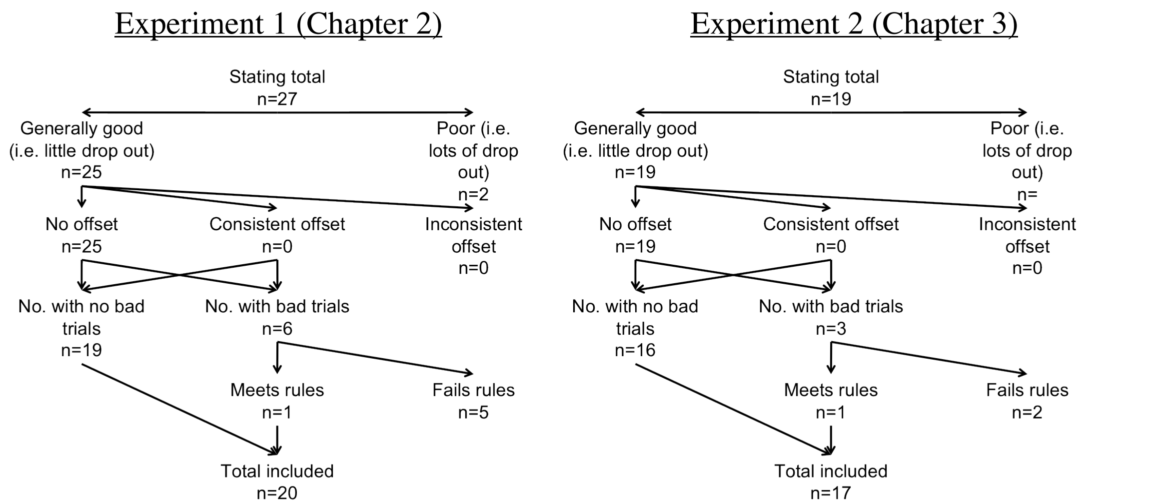


Figure 7-24. Flow chart of data exclusion for the laser condition in experiments 1 and 2.

Table 7-4. Description of any trials in which correction by a conservative rule was employed for the laser condition in experiments 1 and 2.

Participant no.	No. attempts corrected using rules	Participant no.	No. attempts corrected using rules
16	2	N/A	N/A

Gaze Only Trials

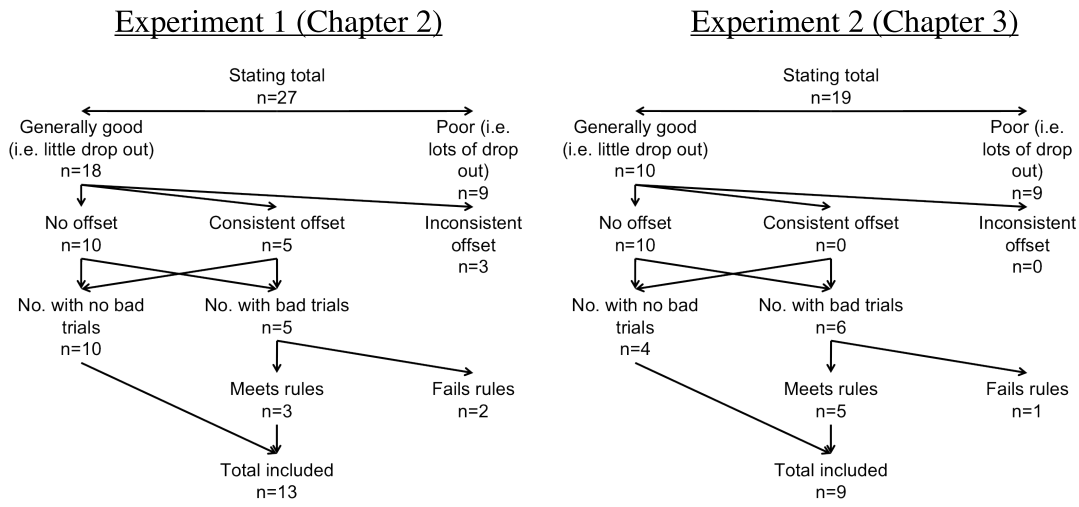


Figure 7-25. Flow chart of data exclusion for the gaze only condition in experiments 1 and 2.

Table 7-5. Description of any trials in which correction by a conservative rule was employed for the gaze only condition in experiments 1 and 2.

Participant no.	No. attempts corrected using rules	Participant no.	No. attempts corrected using rules
10	1	2	2
23	2	4	1
27	2	5	1
		8	1
		13	2

Gaze and Manual Trials

Experiment 1 (Chapter 2) | Experiment 2 (Chapter 3)

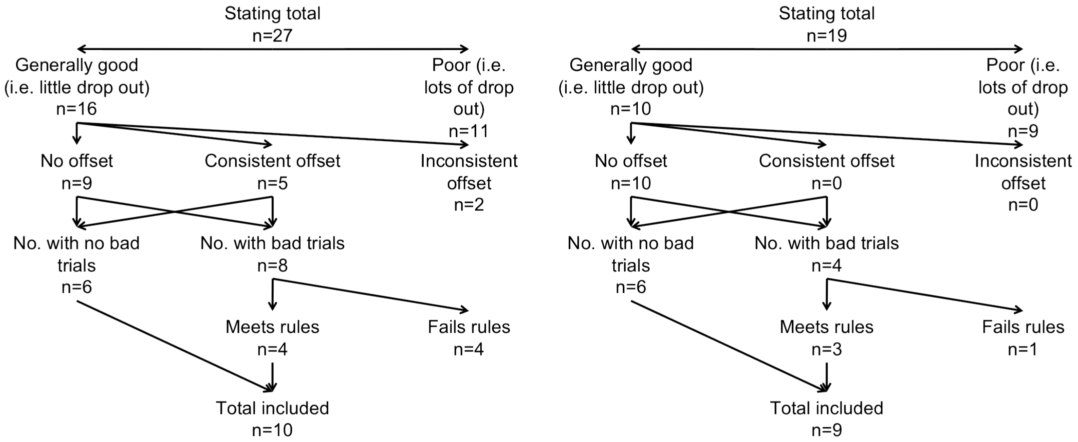


Figure 7-26. Flow chart of data exclusion for gaze in the manual condition in experiments 1 and 2.

Table 7-6. Description of any trials in which correction by a conservative rule was employed for gaze in the manual condition in experiments 1 and 2.

Participant no.	No. attempts corrected using rules	Participant no.	No. attempts corrected using rules
5	3	5	1
10	5	11	2
11	1	13	1
16	1		

Gaze and Laser Trials

Experiment 1 (Chapter 2) | Experiment 2 (Chapter 3)

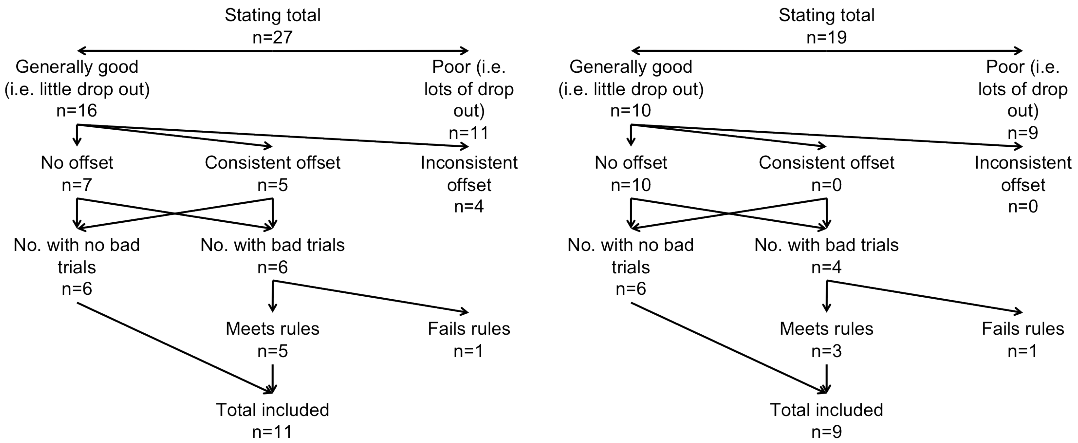


Figure 7-27. Flow chart of data exclusion for gaze in the laser condition in experiments 1 and 2.

Table 7-7. Description of any trials in which correction by a conservative rule was employed for gaze in the laser condition in experiments 1 and 2.

Participant no.	No. attempts corrected using rules	Participant no.	No. attempts corrected using rules
10	1	2	2
16	1	8	1
18	1	11	2
19	1		
27	1		

7.5 Absolute & final error exclusion

Unsigned (absolute/modulus) errors and final errors were not reported for reasons outlined in Chapter 2 Methods 2.2.10. Here I provide illustrative examples to accompany those reasons.

7.5.1 Exclusion of absolute error.

As an example to accompany the reasons for omission of absolute errors I use in-line total position error in the manual tracking condition (Figure 7-28). The absolute (panel A) and the signed (panel B) measures show roughly equal errors for trajectories from 5° left to 45° right but only the signed measure reveals tracking at 90° rightwards to differ from the descending trajectories by trailing the target overall. Crucially, the unsigned errors do not reveal the overall position of tracking relative to the target – ahead for descending targets and behind for horizontally moving and ascending targets. Reference to position time-series plots can indicate this fact but this information is available directly from the signed error.

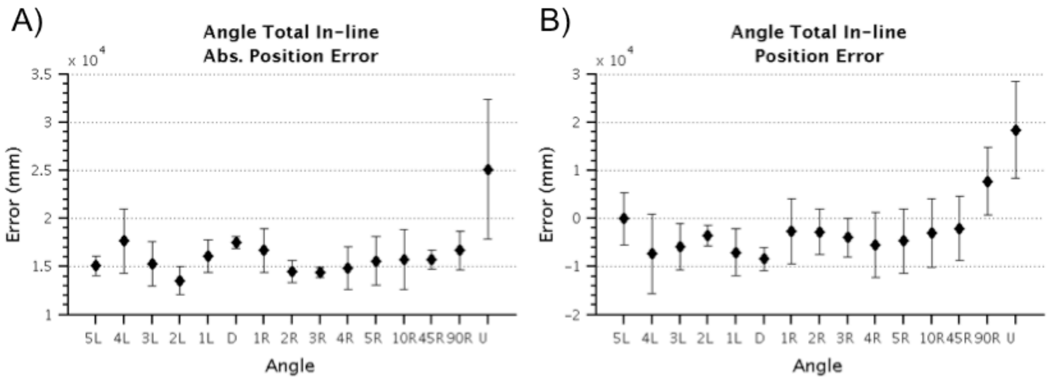


Figure 7-28. In-line total position error for each angle tested in the manual tracking condition. Errors are summed without a sign (A) or with a sign (B).

7.5.2 Exclusion of final error.

As an example to accompany the reasons for omission of final errors I use in-line final and total position error in the manual tracking condition (Figure 7-29). In this example, there is no information available in the final error that is not present in the total error – final (panel A) and total (panel B) error are very closely matched in terms of the distribution of mean errors from zero. Final error for tracking 90° rightwards may give the false impression that tracking is usually ahead of the target whereas in fact tracking was behind the target overall and moved ahead towards the end of the tracking period for only the second and third attempts. This is seen clearly in the time-series for this data (Chapter 2 Results 2.3.3.3 – Figure 2-14). Thus final errors are not useful interpreting tracking behaviour.

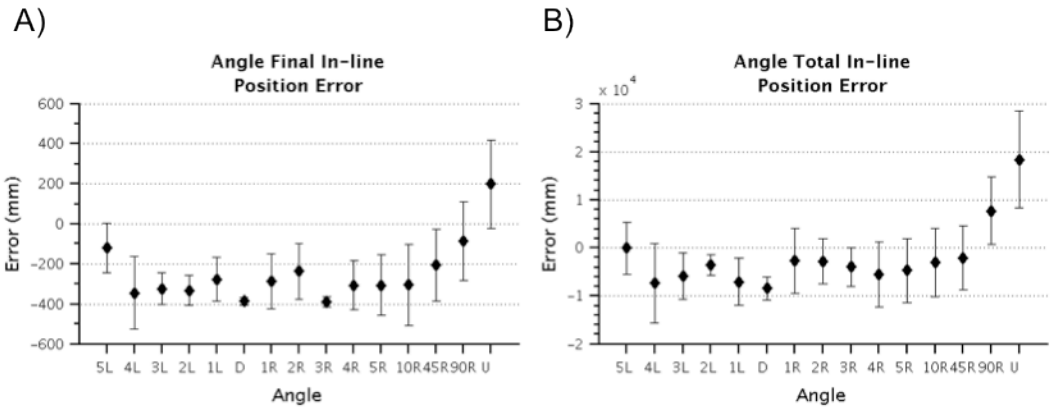


Figure 7-29. In-line final (A) and total (B) position error for each angle tested in the manual tracking condition.

7.6 A side effect of manual tracking and counter-rotation by condition angle

The counter-rotation of condition angle (Chapter 2 Methods 2.2.8) allowed direct comparison of the errors between all angles. However it may introduce bias into the in-line (perpendicular) and sideways (parallel) measures of error for manual tracking because both the fingertip and the target are required in the visual field and so the two cannot overlap. This problem is not present in the laser condition because the tracked position (laser spot) can be superimposed onto the target position without occluding either. When manual tracking, the result is a tracked position offset slightly below (in real world terms) the centre of the target (Figure 7-30a,b&c – Trace 1).

Whilst the target is stationary it would be easy to maintain a tracked position relatively close to the centre of the target. However, when the target is moving one is required to increase the distance tracked below the target in order to ensure that the target remains visible i.e. an increasing safety margin as the target velocity increases. Increasing the distance below the target would not be required when tracking horizontally but a small offset would be expected. This should show in the data as a leftwards tracking error (negative sideways error) somewhat greater than when tracking at other angles though is only apparent in the total position error and not in or the angle time series. It is possible that such an intentional offset did not occur but variability in the small sideways errors may have masked an effect.

The effect is most likely to be noticed when the tracking the ascending target because tracking is rotated by 180° to make it a descending track. Keeping the finger tip and the target in the visual field would require tracking vertically below the target (Figure 7-30b&c – Trace 2) which would show as tracking above the target following rotation by 180º (Figure 7-30c – Trace 3). From the angle time series at 1 ms this does appear to be case as the error for the ascending is approx. 200-250 mm (approx. 200-250 above the target). However. the error for descending targets is typically less -100 mm (less than 100 mm below the target) so the offset resulting from counter-rotation does not appear to be equal for all angles if it is a real effect.

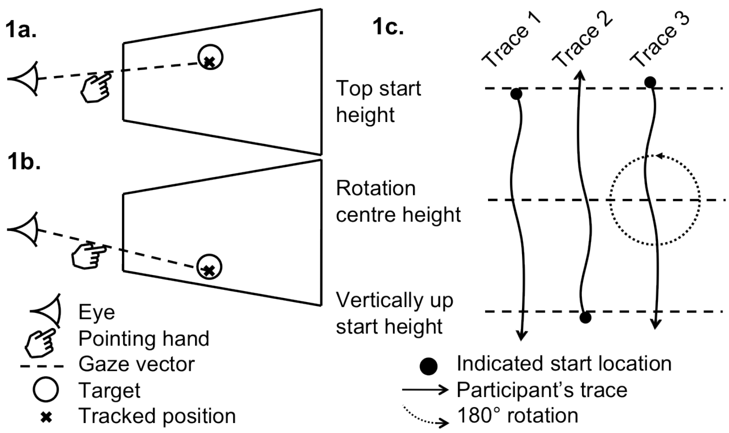
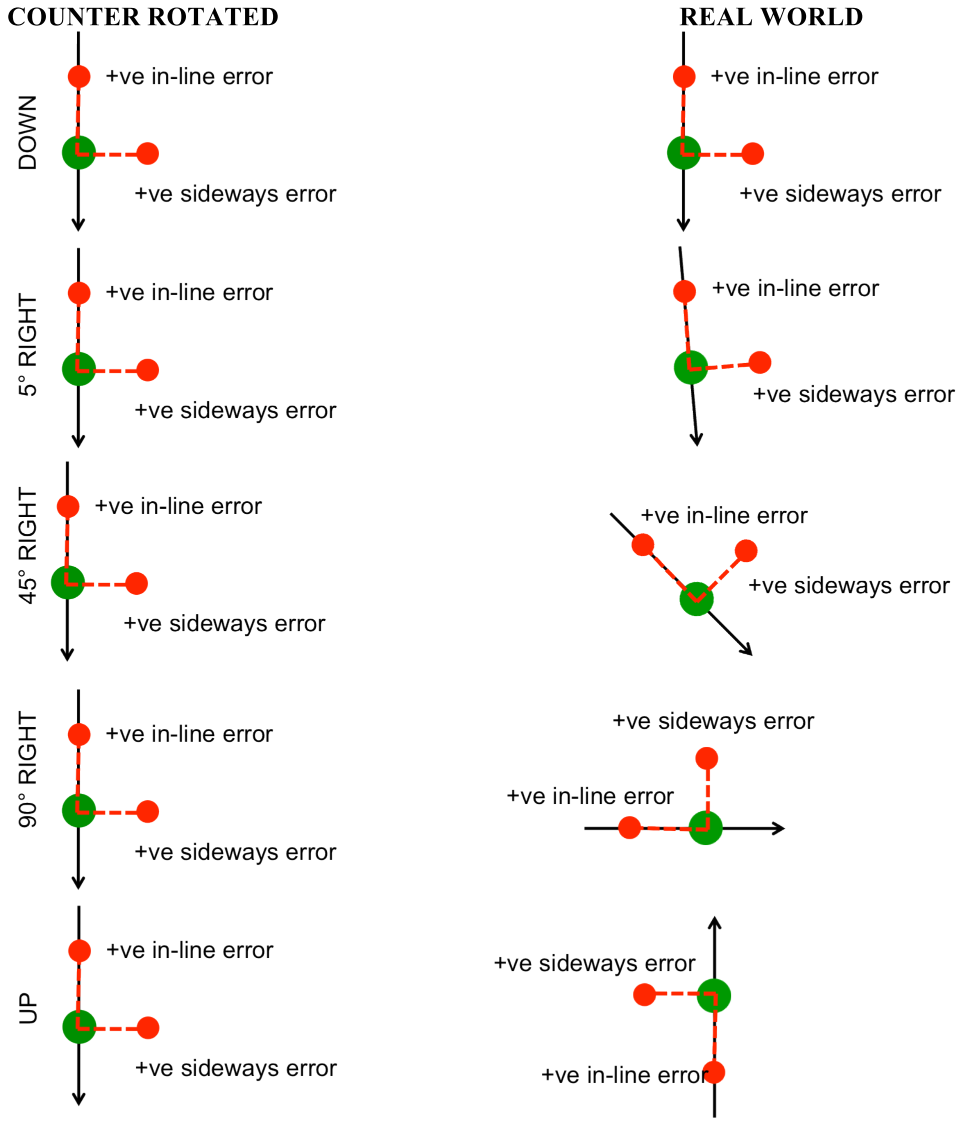
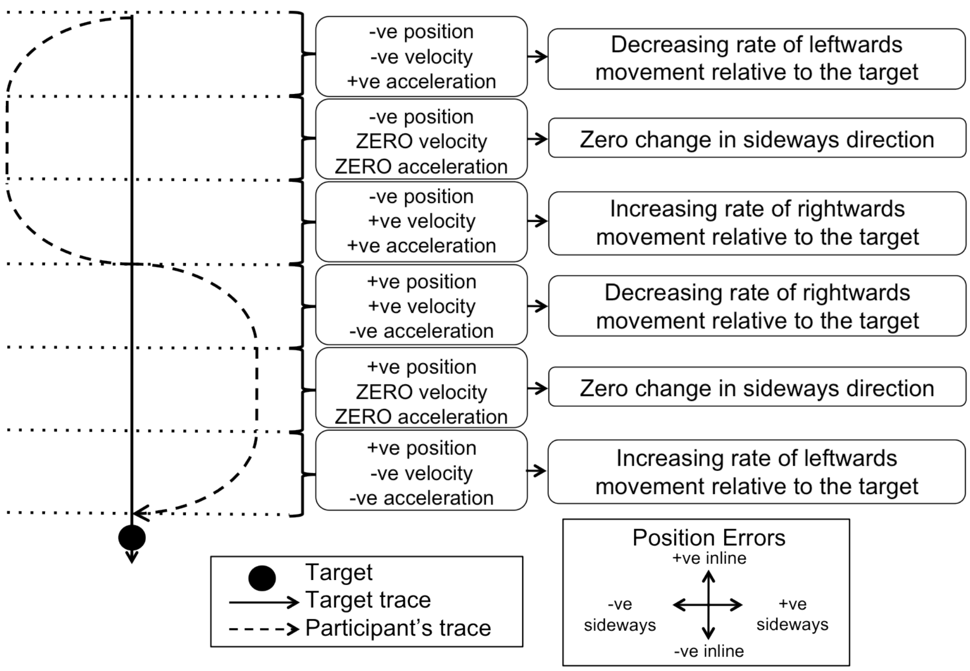


Figure 7-30. Expected manual tracking vector imposed by the manual tracking and effect of 180° counter-rotation on this vector.

Crib Sheet


COUNTER ROTATED
REAL WORLD
DOWN
5° RIGHT
45° RIGHT
90° RIGHT
UP
+ve in-line error
+ve sideways error


-ve position
-ve velocity
+ve acceleration
Decreasing rate of leftwards movement relative to the target
-ve position
ZERO velocity
ZERO acceleration
Zero change in sideways direction
-ve position
+ve velocity
+ve acceleration
Increasing rate of rightwards movement relative to the target
+ve position
+ve velocity
-ve acceleration
Decreasing rate of rightwards movement relative to the target
+ve position
ZERO velocity
ZERO acceleration
Zero change in sideways direction
+ve position
-ve velocity
-ve acceleration
Increasing rate of leftwards movement relative to the target
Target
Target trace
Participant's trace
Position Errors
+ve inline
-ve sideways
+ve sideways
-ve inline