Perception and Awareness of Spatial Orientation Following Transitions in the Availability of Visual Information

by

Jamie L. Voros

B.S., Aerospace Engineering, Massachusetts Institute of Technology, 2016

B.S., Architecture, Massachusetts Institute of Technology, 2016

M.S., Aerospace Engineering Sciences, University of Colorado Boulder, 2020

M.S., Computer Science, University of Colorado Boulder, 2022

A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

Ann and H.J. Smead Department of Aerospace Engineering Sciences

2023

Committee Members:

Torin Clark, Chair

Allison Anderson

Nisar Ahmed

Zachary Kilpatrick

Daniel Merfeld

Voros, Jamie L. (Ph.D., Aerospace Engineering Sciences)

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Thesis directed by Professor **Torin Clark**

Pilots of aircraft and spacecraft experience sudden changes in the availability of visual information during the manual control of aerospace vehicles. For example, visual perceptual cues are suddenly lost when a pilot flies into a cloud. Visual information from flight deck instrumentation is suddenly gained when a pilot's gaze saccades to the attitude indicator. These are just two scenarios describing sudden loss or gain of visual information, both are commonplace during flight. The presence of visual information impacts the accuracy of a pilot's perception of spatial orientation. Further, a pilot may perceive or feel one vehicle orientation, but have an understanding of another orientation based on instrument information which I term "orientation awareness". Pilots must maintain accurate perception or orientation awareness to maintain control of a manually operated vehicle. Therefore, perceptual and orientation awareness dynamics must be well understood for the successful operation and design of crewed vehicles.

A series of experiments were run to characterize the dynamics of orientation perception and orientation awareness following a sudden loss or gain of visual information. Angular velocity perception during earth vertical yaw motion was quantified following a sudden gain and sudden loss of naturalistic visual cues. Human subjects gradually integrated the sudden gain of visual cues over the course of approximately 10 seconds. Past visual cues continued to impact angular velocity perception up to 40 seconds following a sudden loss of naturalistic visual cues. Similarly, tilt perception was quantified following a sudden gain and sudden loss of naturalistic visual cues containing angular velocity and visual horizontality cues. Tilt perception was also quantified following the sudden gain and sudden loss of an attitude indicator (artificial horizon). Again, subjects gradually integrated the new naturalistic visual cue information over a course of approximately 3 seconds. However, human subjects far more slowly integrated the new visual information as presented via an attitude indicator. It took approximately 6 seconds (twice as long) for humans to integrate information from the attitude indicator into their perception of tilt. Past visual cues continued to influence tilt perception for up to 10 seconds following a sudden loss of visual information from both the naturalistic visual cues and attitude indicator. Tilt awareness and tilt perception were quantified following sudden gain and sudden loss of an attitude indicator. In contrast to perception, human subjects immediately integrated the new information from the attitude indicator into their orientation awareness following its sudden appearance. Similarly, past information from the attitude indicator influenced tilt awareness for up to 10 seconds beyond sudden loss of the visual information.

A novel model of orientation perception that is consistent with the data collected in this thesis is presented. Previous models of orientation perception have not been robust to sudden gain or loss of naturalistic visual cues. The use of low pass filtering in the corresponding visual cue pathways (within the model) reconciles differences. In conclusion, this thesis presents empirical quantification of perception and understanding of orientation following sudden transitions in the availability of visual information in addition to a model of orientation perception that is consistent with the data.

Dedication

To all of the fluffy kitties and puppies.

Acknowledgements

I extend thanks to the following University of Colorado Boulder affiliates for their technical contributions: Victoria Kravets, Kieran Smith, Taylor Lonner, Lanna Klausing, Skylar Edwards, Fabrizio Roberts, Jasmin Godinez Rivera, Nadine Poole, Sweta Alla, Nick Boggess, and Jordan Dixon.

The research presented in this thesis was supported by the Office of Naval Research (ONR), though a Multi-University Research Initiative (PI: Daniel Merfeld at Ohio State University).

I thank collaborators working on Spatial Orientation via the ONR MURI for their consistent feedback and technical contributions: Daniel Merfeld, Faisal Karmali, Megan Reissman, and Max Teaford.

I thank the NASA Johnson Space Center Neuroscience Laboratory, specifically Scott Wood, Ajitkumar Mulavara, and Jacob Bloomberg, for donating the Tilt-Translation Sled.

Thank you so much to my advisor, Torin Clark, for always finding a way for me to continue every time the going got tough. I appreciate how many additional researchers you found to operate the TTS and collect SR data while I was physically incapable of doing so myself. I appreciate your flexibility in fitting research around my repeated, varying stages of not being able to walk. Thank you to everyone in the Bioastronautics laboratory for giving me a reason to smile and laugh every time I came into the office. Our office is full of so many genuinely good people and we are so lucky for that. Thanks to Nicole for five years of administrative wizardry. Thanks to Allie Anderson for all her support and mentorship beyond academic input. Lastly, thanks to my family and friends for believing in me.

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Chapter 1

Definitions

The term “orientation awareness” is newly presented in this thesis. Orientation awareness refers to a cognitive level of understanding regarding one’s orientation. Orientation awareness differs from perception in that awareness refers to understanding of an orientation state whereas perception refers to a sensation or feeling of orientation. For example, a skydiver may feel that they are too high to pull their parachute after several seconds of freefall but cognitively be aware that they are truly at 4,000 feet (an altitude at which one may wish to pull their parachute) by inspecting their altimeter. The term “awareness” was chosen due to its existing use by the Airplane State Awareness Joint Safety Analysis Team within the flight deck. It is possible to describe the flight crew as having “lost awareness” of their aeroplane’s state when referring to a flight crew that does not know (perceptually or cognitively) what motion the aeroplane is currently engaged in [Schnell et al., 2017]. Similarly, during skydiving operations within the United States, “awareness” is used to describe cognitive understanding of one’s altitude. To become licensed, a student jumper must demonstrate apt “altitude awareness” during freefall [USPA, 2023]. Altitude awareness during freefall refers to maintaining understanding of one’s altitude via inspecting an altimeter.

Chapter 2

Motivation

2.1 Dangers of Spatial Disorientation

Spatial orientation in humans refers to perception of location in three-dimensional space, our angles of roll, tilt and yaw, and any motion we are currently engaged in [Benson, 1978] [Merfeld, 2017]. Such an understanding is necessary for any task involving self-motion, such as flying a plane or spacecraft [Gillingham and Previc, 1993]. While humans generally perceive orientation well [Guedry, 1974], some unusual motions [Clark et al., 2015a] [Tribukait et al., 2016] or environments [Clark et al., 2019] [Clément et al., 2007] [de Winkel et al., 2012] [Oman, 2007] can cause misperception of orientation, or spatial disorientation. Spatial disorientation in pilots is considered a leading source of aviation mishaps in both fixed wing and rotary aircraft [Bellenkes et al., 1992] [Young et al., 2003]. An example of becoming spatially disoriented can occur during take-off on a commercial flight. During take-off, a commercial jet aircraft must accelerate linearly. Such forward linear acceleration is indistinguishable (to otoliths of the vestibular system and any other graviceptors) from pitching backwards and can create a sensation of pitch tilt while the aircraft is still level on the runway. In such a scenario, the pilot must refrain from pitching the aircraft downwards in order the counter the spurious sensation of backwards tilt elicited by linear acceleration.

The brain making misinterpretations of sensory cues when exposed to novel motions (those not naturally experienced in everyday, terrestrial activities) is expected [Young et al., 2003].

2.2 Why Understanding Spatial Orientation is Necessary for Preventing Disorientation

To prevent spatial disorientation, one must first understand why it happens. Developing and validating models of orientation perception that are consistent with experimental data, it is then possible to simulate scenarios that are not feasible to test in a laboratory. When a model is consistent with data for known, similar, scenarios, we may be able to use it to predict dynamic motions resulting in spatial disorientation that can become deadly.

2.3 Limitations of Existing Work

We have a thorough understanding of both the functionality and limitations of the vestibular system[Clark et al., 2019] [Guedry, 1974] [Merfeld, 2017] [NASA, 2004] and a general understanding of typical spatial disorientation illusions which occur when visual cues are unavailable [Bellenkes et al., 1992] [Benson, 1978] [Braithwaite et al., 1997] [Cheung et al., 1995] [Cohen, 1977]. However, existing models lack the ability to accurately predict spatial orientation in scenarios that occur in more operational environments [Dixon et al., 2019]. For example, aviation mishaps are often associated with scenarios where visual cues rapidly degrade (e.g., flying into a cloud) despite the presence of flight instruments. This motivates studying scenarios where the availability of visual cues or instrument information suddenly change.

2.4 Summary

Spatial disorientation is a major risk factor for aviation mishaps. Such mishaps tend to have extreme consequences (fatalities) [Bellenkes et al., 1992] [Benson, 1978] [Braithwaite et al., 1997] [Cheung et al., 1995] [Durnford et al., 1995]. Therefore, preventing spatial disorientation is of upmost importance. In order to prevent or reduce the occurrences of spatial disorientation, we first must understand how humans perceive orientation. We must also understand the impact that information from available instrumentation has on orientation perception. By creating computational models of spatial orientation perception (feeling of orientation) and orientation awareness (understanding of orientation) that is consistent with measured orientation perception data from humans, we are better able to understand central nervous system and brain processing of sensory cues and instrument information.

With a thorough understanding of how we perceive orientation and what instrumentation can do to limit spatial disorientation, we are better equipped to identify failure modes (e.g., motions that induce critical spatial disorientation). By modelling spatial orientation, we may be able to prevent mishaps that result from them [Dixon et al., 2022]. Understanding spatial orientation additionally has uses in better designing virtual reality (VR) experiences. It may become possible to perform self-motion in VR that results in orientation perception consistent with orientation in the virtual environment despite limitations on which sensory channels are used (e.g., using visual and auditory channels but not vestibular).

Chapter 3

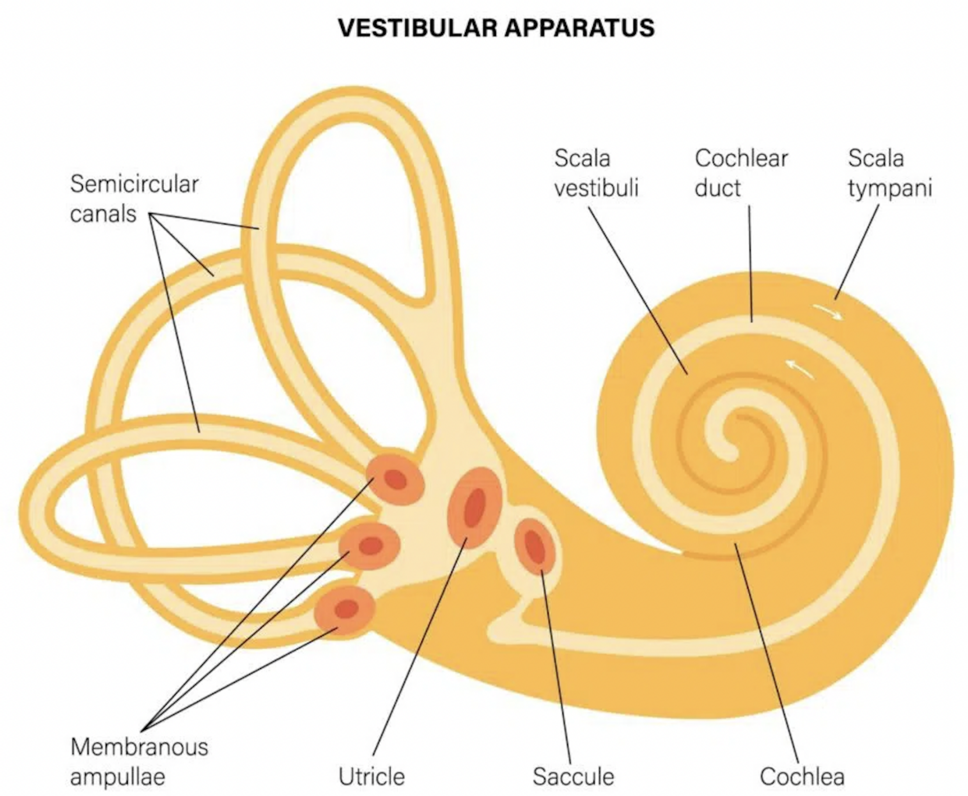
Background

3.1 The Vestibular System

The vestibular system consists of three semicircular canals and the otolith organs in each ear. The semicircular canals are approximately perpendicular to each other and sense angular velocity in 3 planes of motion [Goldberg and Fernandez, 1971] [Grossman et al., 1988] [Hartshorne et al., 2021]. The otolith organs are largely responsible for sensing linear acceleration (which includes linear acceleration due to gravity) [Fernández and Goldberg, 1976].

The semicircular canals contain hair cells which change the electrical impulses the produce when stimulated by the endolymph (a fluid) as a result of head movement. The electrical impulses are sent to the vestibular nuclei which sends the signal to the muscles that move the eyes and the cerebellum [Hartshorne et al., 2021]. Eye movement in the opposite direction of movement may occur as a result of semicircular canals stimulation; this is known as the vestibulo-ocular reflex [Merfeld, 2017]. If the eyes move to the extent of their most extreme position (e.g., looking as far left as possible) while such an electrical signal continues, a rapid movement will bring the eye back to its central position before returning to the pattern of moving opposite to the sensed motion. The rapid movement is referred to as nystagmus. The semicircular canals have a key limitation: although they can accurately transduce motions which are short in duration, if the head rotates at a constant angular velocity, the endolymph fluid's angular motion relative to the head decreases and thus the signal decays during longer, constant, or slowly changing rotations [Laurens and Angelaki, 2011].

Figure 3.1: Diagram of the Vestibular System [Kashouty, 2011]



In addition to the peripheral dynamics of the semicircular canals, there is additional central processing called "velocity storage." It is a result of the aforementioned signal decay which has been shown in monkeys [Raphan et al., 1979]. Prolonged exposure to constant velocity angular in darkness results in nystagmus decay to nothing [Raphan et al., 1979] followed by nystagmus immediately after termination of rotation [Merfeld et al., 1993a] [Raphan et al., 1979]. Notably, nystagmus decay is slower than signal decay from the afferent neurons [Laurens and Angelaki, 2011] [Raphan et al., 1979]. In light, however, there is no nystagmus decay and, similarly, no nystagmus once the motion has ended [Raphan et al., 1979].

The otolith organs have two components: the saccule and utricle. The otolith organs sense linear acceleration and tilts in all planes via the macula (found on both saccule and utricle) which contains hair cells (and other supporting cells)[Purves and Williams, 2001]. The otolithic membrane sits atop the hair cells and contains crystals of calcium carbonate which make the membrane heavier than the tissues surrounding it [Purves and Williams, 2001]. During periods of linear acceleration or tilt, the membrane shifts relative to the hairs causing a shear force between the membrane and macula [Purves and Williams, 2001]. The utricle is approximately horizontal and senses accelerations in the left, right and fore, aft directions. The saccule is approximately upright and senses accelerations in the up, down directions [Purves and Williams, 2001]. The proposed research uses linear accelerations in the left or right directions and roll tilt, therefore stimulation to the utricle, utricular shear, is most important.

Unlike the semicircular canals, there is little signal decay during prolonged periods of linear acceleration [Fernández and Goldberg, 1976]. Further, it is possible to construct simultaneous earth horizontal roll tilt and left-right linear acceleration profiles such that the roll tilt cancels out linear acceleration that would have come from left, right translation [Angelaki and Yakusheva, 2009].

3.2 Orientation Perception in Humans

Humans use cues from multiple sensing modalities to perceive orientation [Dai et al., 1989] [Fetsch et al., 2012] [Karmali et al., 2014] [Newman, 2009]. Previous work has focused on the integration of only visual and vestibular cues to predict orientation perception [Newman, 2009], however other work has incorporated tactile cues [Dai et al., 1989] and auditory cues [Shayman et al., 2020]. This thesis focuses on building upon a model of orientation perception [Newman, 2009] that uses visual and vestibular cues only. It has been possible to accurately predict orientation perception in many scenarios with only these two cues [Clark et al., 2015a] [Clark et al., 2019] [Clark et al., 2015b] [Merfeld, 2003] [Merfeld et al., 1993b] [Zupan and Merfeld, 2003]. Saliently, for the piloting use case, vestibular and visual cues are the main two cues typically available in an aerospace environment.

3.3 Vestibular Sensing

The vestibular organs sense angular velocity (semicircular canals) and linear acceleration (otolith organs) [Gillingham and Previc, 1993]. Angular velocity information (from the semicircular canals) can be used to determine whether we are actively rotating in space. Linear velocity information (from the otolith organs) is used both to determine linear acceleration due to self-motion as well as linear acceleration due to gravity. Occasionally disorientation can occur due to the potential ambiguity in vestibular system afferents. For example, when one experiences large linear acceleration (e.g., during take-off in a commercial aircraft). The resulting net linear acceleration (a combination of both gravity and forwards acceleration) can cause an illusory sensation of tilting backwards because the otolith organs cannot disambiguate between linear acceleration due to gravity and linear acceleration due to motion in space [Clément et al., 2001] [Corbett and Enns, 2006] [Gillingham and Previc, 1993] [Querner et al., 1999].

3.4 Visual Sensing

When visual cues are available, humans use their eyes as a major component of determining spatial orientation [Gillingham and Previc, 1993]. Trees, buildings, and a horizon give a visual cue as to the direction of gravity with respect to the observer. In motion, movement of a visual scene elicits sensations of linear velocity, angular velocity, and linear acceleration [Dichgans et al., 1972]

[Held et al., 1975] [Warren et al., 1988] [Warren et al., 1991]. Lastly, visual markers or known landmarks (such as a target) provide position cues.

3.4.1 Optical Flow

Optical flow refers to perceptual visual cues that come from movement of a visual scene (e.g., the exterior world appearing to be moving past a passenger on a train) [Dichgans and Brandt, 1973] [Held et al., 1975] [Warren et al., 1988] [Warren et al., 1991]. Optical flow does not necessarily have to be in a single plane; optical flow can indicate linear velocity [Lamontagne et al., 2007], heading [Warren et al., 1988] and indicate angular motion [Voros and Clark, 2023]. Experimentally optical flow can be induced by a moving dot pattern [Voros and Clark, 2023].

3.4.2 Visual Vertical and Horizontal

Visual vertical and horizontal are artifacts of a visual scene which give cues as to the direction of gravity (and thus roll or pitch tilt) [Mast and Jarchow, 1996] [Vingerhoets et al., 2007] [Vingerhoets et al., 2008]. A horizon is an example of a visual horizontal cue, a horizon provides roll (horizontal angle of the horizon) and pitch (depth of the horizon or attitude) tilt cues [Mast and Jarchow, 1996]. Trees and buildings are examples of verticality cues which can provide a sense of roll tilt [Vingerhoets et al., 2008].

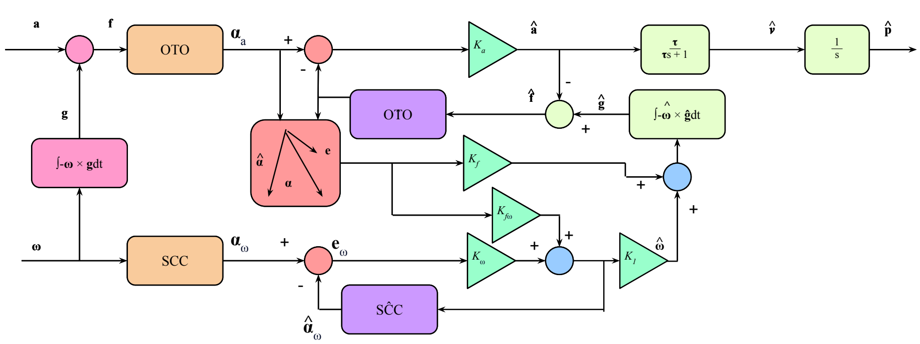
3.5 Existing Models of Orientation Perception

Families of models of orientation perception have existed for decades [Borah et al., 1977] [Borah and Young, 1983] [Clark et al., 2019] [Young et al., 2001], so in the interests of conciseness, the review here will focus only on models directly related to the proposed thesis. For more details, Clark et al., [Clark et al., 2019] provide a more complete review of efforts to model orientation perception.

3.5.1 3D Modelling of Orientation Perception and the Observer Model

In 1993, Merfeld et al., proposed and implemented an observer model [Luenberger, 1971] of spatial orientation in monkeys. The model itself is presented in several different forms. I am most interested in the 3-dimensional model of spatial orientation that takes into account linear and angular velocity in 3 dimensions to estimate orientation. The 1993 [Merfeld et al., 1993a] model captures orientation perception in the presence of vestibular cues only. Internal models are neural representations that replicate physical relationships or dynamics. Via the internal model, the model predicts sensory afference which is subtracted from true sensory afference to produce sensory conflict. The sensory conflict term is then used to update the predicted perception of orientation. Velocity storage is an example of an internal model: although the signal from the semicircular canals decays very quickly our "inverse internal model" of orientation perception takes into account the limitations of the SSCs and thus perception of orientation decays more slowly. Without an infinite feedback gain, the true motion is not fully re-constructible in the extended angular velocity scenario [Karmali, 2019].

Figure 3.2: Multi-dimensional sensory conflict model of orientation perception based on vestibular cues only as presented in 1993. Updated to include perceived velocity ($\hat{v}$) and perceived position ($\hat{p}$). [Merfeld et al., 1993a] [Newman, 2009]



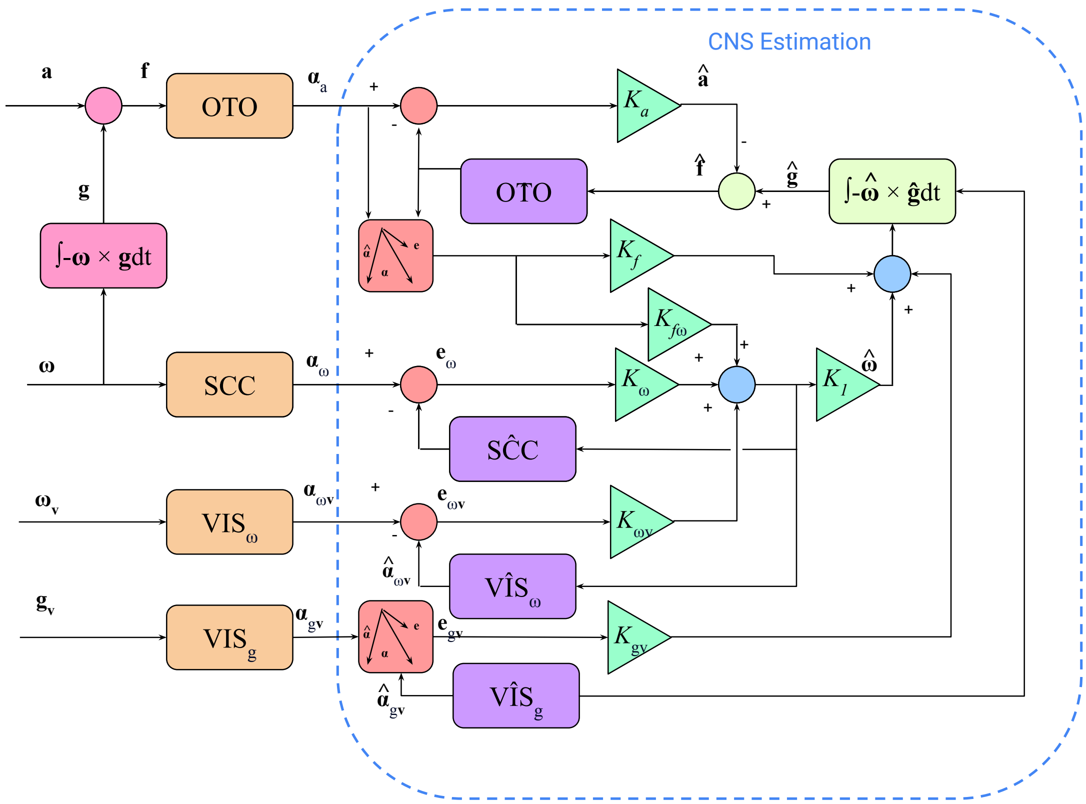
The model shown in Figure 3.2 [Merfeld et al., 1993a] is the core vestibular only model in the class of orientation perception models discussed in this document. The model starts with body dynamics to produce physical motions experienced by the simulated individual's head. These are then processed by vestibular sensors, which define sensory afferents outputted by transfer function models of the semicircular canals and otolith organs (see "Sensory Dynamics" box in Figure 3.2). Sensory Dynamics accounts for transduction processing such as the decay of semicircular canal signal during prolonged, constant angular velocity stimulation. The S_{acc} transfer function (a high pass filter with time constant of 6 seconds) accounts for that decay. The S_{oto} transfer function (in this particular model) is unity. Lastly, this information is fed into an internal model of body dynamics and an internal model of sensory dynamics. The internal model of sensory dynamics is a transfer function which turns the signal from an expectation of sensory measurements that can be differenced with the actual information received from the sensory organs.

3.5.2 Observer Model with Visual Cues

In 2009 Newman [Newman, 2009] added visual cue pathways to Merfeld's 1993 model of orientation perception. Different from the vestibular cues, however, visual cues can be turned on and off via gating (for example, shutting one's eyes results in total removal of visual cues). Vestibular cues have no such gating because vestibular cues always persist. The visual cue gating allows the model to produce a prediction of orientation perception during a sudden change in visual cue availability, however, the instantaneous nature of the gates results in a discontinuity in such a scenario.

The Newman model, shown in Figure 3.3, shows two types of visual cues added to the core vestibular-only model from Figure 3.2. The visual cue inputs are passed through transfer functions (orange boxes in Figure 3.3) representing sensory dynamics. Like the vestibular portion of the model, each visual pathway incorporates differencing of the internal model expectation of that cue (purple boxes in Figure 3.3). The exact model presented in Newman's 2009 thesis contains additional visual pathways (visual linear position and velocity cuing). However, the motions and cues provided during experimentation in this thesis do not use either visual position or linear

Figure 3.3: Multi-dimensional sensory conflict model of orientation perception based on visual and vestibular cues [Newman, 2009].



velocity pathways. Therefore, these two visual cuing pathways have been omitted from figures appearing in this thesis.

Chapter 4

Investigative Rationale

Maintaining apt spatial orientation is important in the manual control of aircraft. It is, therefore, important to understand when human may misperceive their orientation. Existing literature on spatial orientation during sudden transition in the availability of naturalistic visual cues or information (e.g., instrumentation) is incomplete. In this thesis, I have quantified orientation perception during sudden transitions in the availability of naturalistic visual cues and during sudden transitions in the availability of an attitude indicator. I present a novel model of orientation perception that is robust to sudden changes in naturalistic visual cue availability. Lastly, I have quantified orientation awareness during sudden transitions in the availability of an attitude indicator. Taken together, this thesis bridges gaps both in the measurement and modelling orientation perception and in the measurement of orientation awareness. Awareness and perception are important to better understand how and when disorientation or misunderstanding of orientation might occur in flight scenarios where visual cues or instrumentation may suddenly appear or disappear (e.g., when flying into or out of a cloud or looking away from an instrument display).

4.1 Gaps in the Literature

4.1.1 Gap One: Impact of Dynamic Availability of Visual Cues on Perception

Sudden transitions in the availability of visual cues are a common occurrence in aviation operations. Flying into a cloud is a common enough occurrence for there to exist explicit rules for avoiding clouds during flight without an instrument rating for pilots, skydivers, and paragliders in the United States [USPA, 2023]. Similarly, flying out of a cloud, and therefore receiving sudden visual cue information, is a common occurrence in earth bound flight operations.

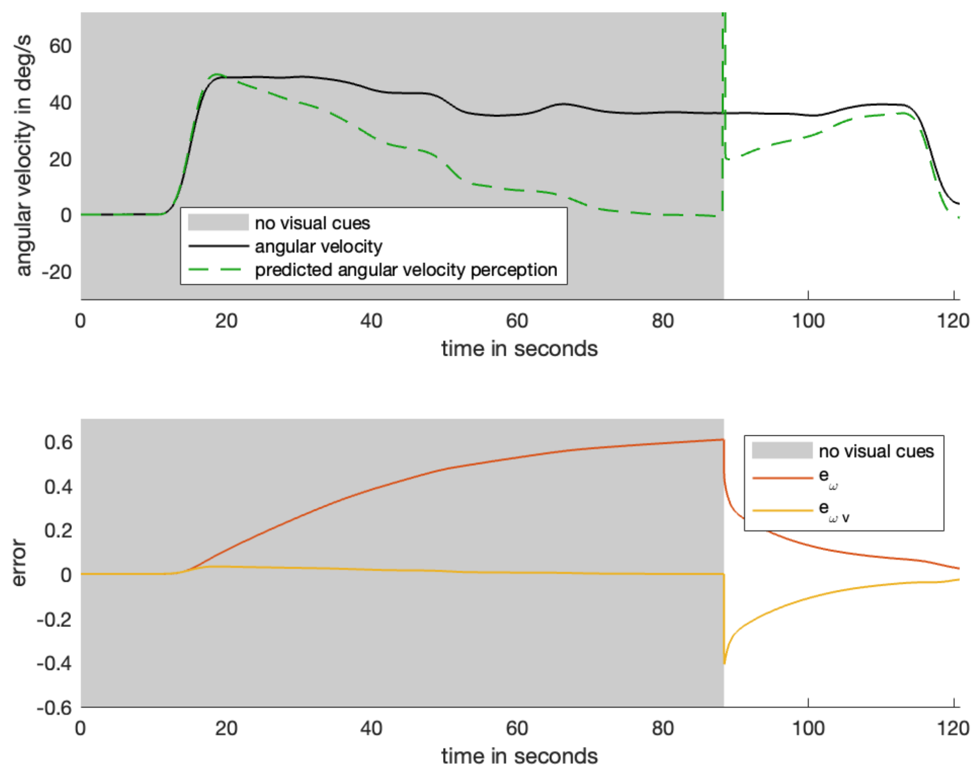
Flight operations involve complicated combinations of motion (e.g., linear accelerations and decelerations coupled with angular accelerations and decelerations). However, to appropriately measure, model and ultimately understand orientation perception, we must first start with a simplified case. During Earth-vertical yaw rotation, the only stimulation to the vestibular system is to the semicircular canals. Without roll, pitch or linear motion, there is no change in stimulation to the otolith organs. Via Earth-vertical yaw motion, it is possible to study the integration of visual angular velocity cues with the semicircular canals only. Beyond Earth-vertical yaw motion, roll tilt and lateral translation can be used to study the integration of visual cues in the case where both the otolith organs and semicircular canals having changing stimulation.

4.1.2 Gap Two: Models that Can Process Dynamic Availability of Visual Cues

The most recent version of the observer model [Newman, 2009] does not accurately predict spatial orientation during transitions in the availability of visual cues. Figure 4.1 details one example of the current observer model predicting a discontinuous perception of motion during a visual transition. The discontinuity occurs as a result of a step (sudden visual transition) in visual cue availability during a period where orientation perception and true motion are incongruent. The sudden appearance of visual cues causes a discontinuity in the sensory-conflict portion of the model (shown in Figure 4.1, bottom panel).

Given the prevalence of visual transitions in aviation and lack of existing literature on orientation perception following such a transition, it is important that existing models of orientation perception be updated to handle them.

Figure 4.1: Existing Observer Model output during a sudden appearance of visual cues. Error (y-axis, lower plot) in radians per second.



4.1.3 Gap Three: Impact of Dynamic Transitions in Availability of Instrument Display on Orientation Awareness and Orientation Perception

Artificial orientation cues (outside of those that occur naturally from physical or environmental motion) can result in orientation awareness that differs from purely perceptual orientation. For example, an attitude indicator gives the user a cognitive (and not perceptual) awareness of their tilt. Currently, scientific literature does not capture how orientation awareness and perceptual orientation interact or differ.

When a pilot is flying based on instrument information, the pilot is typically unable to fix their gaze on a single instrument. During instrument flight rules, pilots must use information from several instruments at once. Pilots' gaze must saccade between different instruments. Therefore, it is important that we measure orientation awareness during sudden transitions in the availability of instrument information. There is no existing literature that captures orientation awareness during such a scenario.

Chapter 5

Specific Aims

The three gaps identified in scientific literature give rise to the following three aims. Note that while the three specific aims do not perfectly mirror the three identified gaps but, when taken together, the three aims cover all the scientific questions posed by the three gaps in the literature.

5.1 Summary of Specific Aim One

The first aim of this thesis was to collect data from human subjects on their perception of their orientation and self-motion during and following visual transitions in yaw motion. I designed three motion profiles (earth vertical yaw motion only) such that subjects misperceive their orientation without visual cues but accurately perceive their orientation with visual cues. The motion profiles were designed to stimulate semicircular canal response only. I collected perception data in two control conditions (visual cues always available, no visual cues available) and in two test conditions (visual cues suddenly appearing, visual cues suddenly disappearing). Once I had collected the requisite data, I extended the Newman (2009) Observer model to better capture the empirically observed perceptual dynamics following a transition in the availability of visual cues.

5.2 Summary of Specific Aim Two

The second Aim builds upon Specific Aim One. In Specific Aim One, I had purposefully chosen a motion (Earth-vertical yaw motion) that isolated semicircular canal stimulation. In Specific Aim Two, I measured roll tilt perception because such motion results in changing stimulation to both the semicircular canals and otolith organs. Thus, using a combination of roll tilt and translation, it was possible to examine perception following sudden transitions in visual cue availability while sensory cues from both types of vestibular organs were being integrated. I designed three motion profiles that were a combination of roll tilt and translation that resulted in misperception of tilt when visual cues were absent. I collected perception data in two control conditions (1. visual angular velocity and horizontality cues present, 2. no visual cues present). I collected data in two test conditions (visual cues suddenly appearing, visual cues suddenly disappearing). Therefore, more than one visual motion pathway can be stimulated. In order to build an accurate model, I wish to stimulate one (additional) visual pathway at a time to make appropriate model changes.

As in Specific Aim One, once I had collected data for roll tilt perception, I made further revisions to the model presented at the conclusion of Specific Aim One. The final model presented produced predictions that were consistent with experimental data for roll tilt perception presented in Specific Aim Two.

5.3 Summary of Specific Aim Three

In Specific Aim Three, I quantified orientation perception and orientation awareness during sudden transitions in the availability of pilot instrument cues.

I used the same three motion profiles that I had designed in Specific Aim Two. Specific Aim Three had two control conditions (no visual or instrument cues and cues from an attitude indicator) and two test conditions (sudden appearance of an attitude indicator, sudden disappearance of an attitude indicator). Aim Three had two dependant variables (orientation perception and orientation awareness) per test condition.

5.4 Additional Note

All experimental procedures presented in this thesis were approved by the Institutional Review Board at the University of Colorado Boulder under protocol 19-0303. Informed consent was obtained from all participants prior to any testing.

Chapter 6

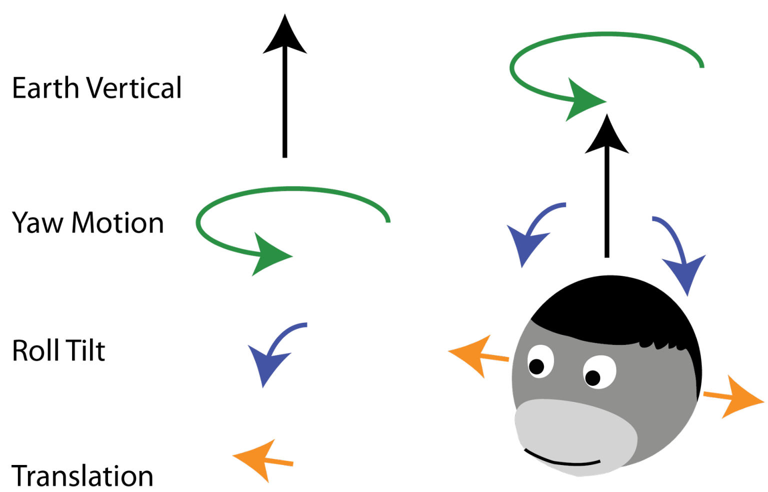
Specific Aim One

6.1 Introduction

I measured perception of angular velocity during earth vertical yaw motion. When visual cues were provided, subjects were provided with visual angular velocity cues only.

I present a novel model of orientation perception that is consistent with data collected in the first part of Specific Aim One.

Figure 6.1: Diagram to show different types of motions that subjects experienced.



6.2 Experimental Methods

6.2.1 Task

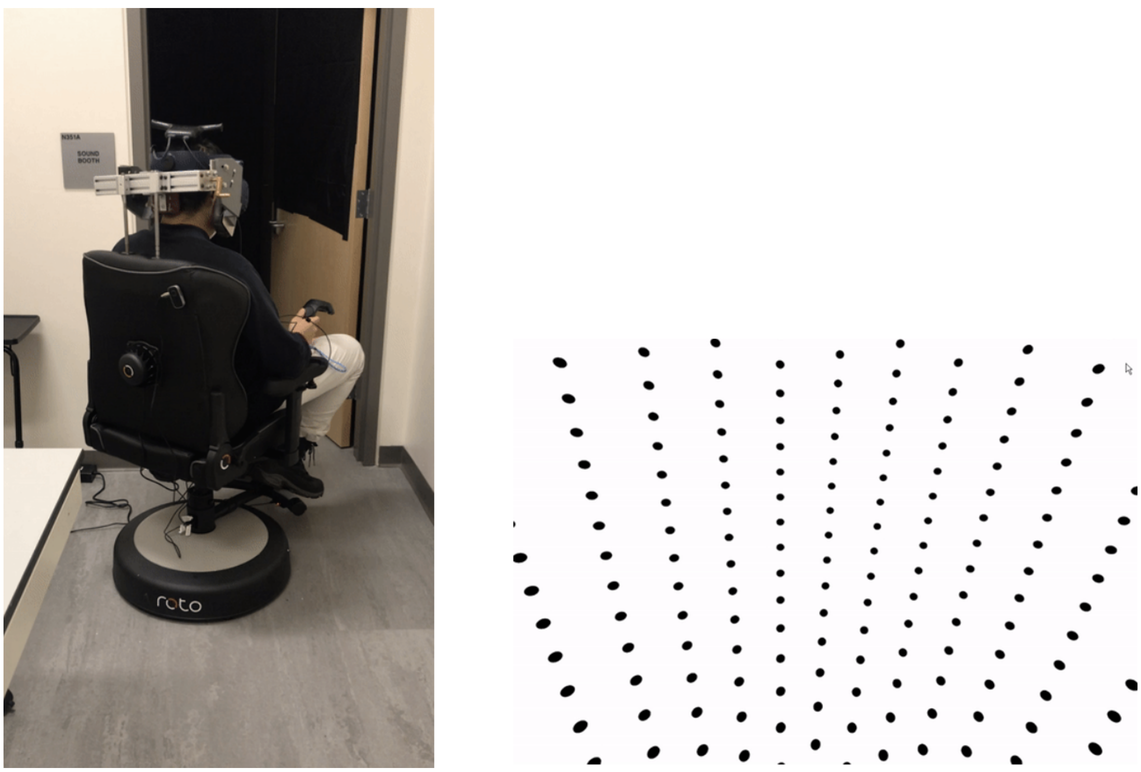
Subjects were seated a chair which rotated about an Earth-vertical yaw axis *(RotoVR, Borehamwood, UK)*. The chair was adapted to contain a head restraint (Figure 6.2) to ensure subjects' head motion (and thus stimulation to the vestibular organs) was consistent with chair movement. Visual cues were provided by a wireless virtual reality (VR) head mounted display (HMD) *(HTC, New Taipei City, Taiwan)*. The provided visual cues were always congruent with true motion.

Within the HMD, subjects were "inside" a large sphere with a dot pattern on the inside, shown in Figure 6.2. Note that the view shown in Figure 6.2 is prior to distortion applied when the image passes through the lenses of the HMD. The visual scene provided optical flow but did not include any cues regarding Earth-horizontal or angular position (e.g., azimuth).

Subjects reported their dynamic perceptions of yaw motion by pressing the thumbpad of an *HTC Vive* controller in their left/right hand every time they felt like they had rotated 90 degrees left/right. Subjects held the triggers on the back of the controllers if they felt they were not moving. Based on subject responses, it was possible to calculate inferred angular velocity by relating the time between thumbpad presses and 90 degrees. The task of indicating rotation every 90 degrees has been employed and validated previously [Groen and Jongkees, 1948] [Guedry and Montague, 1961].

White noise was provided via the HMD headphones to mask spurious auditory cues (e.g., laboratory noises coming from one corner of the space). The chair was set to rumble to a white noise profile to greatly reduce any tactile cues (mild vibration of the chair's motors during motion) to help isolate visual and vestibular cues. Lastly, the experiment occurred in a darkroom to reduce the impact of stray light entering the HMD and thus impacting image sharpness or immersion [Zhan et al., 2020]. The room lights are on in Figure 6.2 only for demonstration purposes.

Figure 6.2: Left: Model seated in experimental apparatus. Right: Dot pattern shown inside HMD.



6.2.2 Experimental Design

Subjects completed a pre-screening questionnaire. Exclusion criteria were any known issues of vestibular dysfunction, a Motion Sickness Simulator Questionnaire score above the 90th percentile, age under 18 or over 40, and requiring glasses for 20/20 vision. Subjects requiring glasses for 20/20 vision were excluded because the HMD was not compatible with glasses, contact lenses were acceptable. Subjects highly susceptible to motion sickness were excluded as the goal was not to cause subjects discomfort. Subjects over 40 were excluded due to changes in vestibular sensing associated with age [Bermúdez Rey et al., 2016]. Several subjects were excluded based on their need to wear glasses and one was excluded due to age; none were excluded based on the other exclusion criteria. Not all subjects completed testing and each motion profile included data from at least 6 unique subjects. Not all subjects completed a full course of testing for two reasons: 1) I added an additional motion profile that was highly variable in nature after examining data from the first 6 subjects. I performed a second round of data collection specifically to collect data on this motion profile. Not all subjects returned for the second round of data collection. 2) Several subjects (3) dropped out part way through testing due to cybersickness.

I used three unique motion profiles, see Figure 6.3, designed to elicit misperception of angular velocity without visual cues. Each subject experienced each motion profile at most four times, each time with one of the four different visual cue availability condition. I call each combination of motion profile and visual cue availability condition a "trial." In order to account for differences in angular velocity perception to the left and to the right, each subject was randomly assigned an initial direction of motion per profile. This means that, for each motion profile, about half the subjects experienced a flipped version of the motion profile (e.g., rotating left instead of right). However, every time the same subject experienced the same motion profile (with different visual cue availability), the motion was in the same direction.

The different visual cue conditions were as follows:

- Visual cues for the entire duration of the profile (control condition)

- No visual cues (control condition)
- Visual cues at the beginning, sudden loss of visual cues part way through (test condition)
- No visual cues for the initial part of the motion and sudden gain of visual cues which lasted the remainder of the profile (test condition)

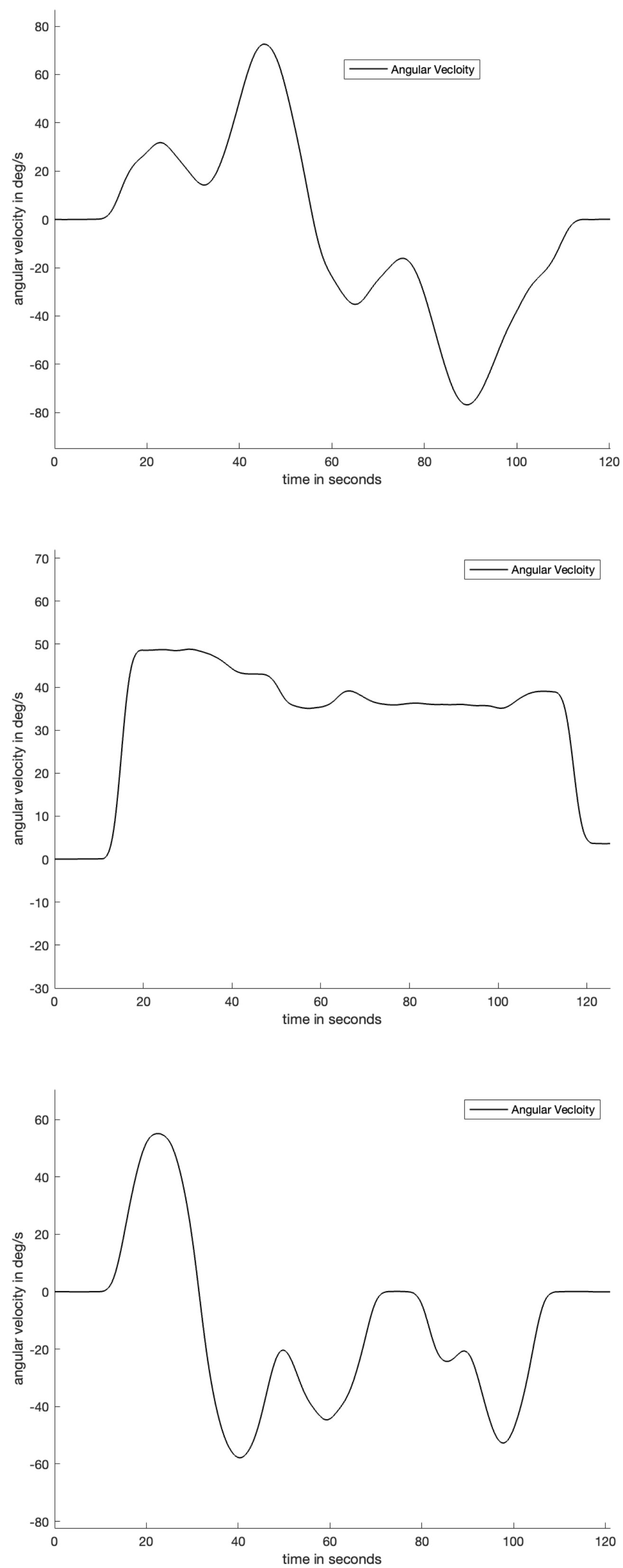
During periods of "No visual cues," subjects still wore the HMD which provided a blacked-out display. The lights remained off in the darkroom such that as little light as possible entered the HMD. One motion profile had two different visual scene transition times (some subjects experienced the visual transition for this motion profile near the end of the motion and others near the beginning of the motion). These are considered two different test conditions even though the same underlying motion profile was used.

6.2.3 Test Procedure

Seventeen unique subjects participated in testing (7 female; mean age 30 SD $\pm$ 5 years; 15 white and 2 more than one race). No subjects completed the full course of testing. This is because additional test conditions were added later and it was not possible to recall all previous participants for a second testing session. Three subjects did not complete testing due to cybersickness. Subjects first completed 4 practice trials to familiarize themselves with the psychophysical task, visual scene, and Earth-vertical rotation they would experience during the experiment. All subjects had the opportunity to complete more practice trials, but none obliged. Responses to the first practice trial (constant angular rotation in one direction) were inspected to ensure the subject understood the task. Criteria was ensuring that the subject had pressed the appropriate thumbpad at a consistent rate during the practice trial.

Subjects then completed the course of testing, each trial and visual cue availability condition appearing in a randomized order. Subjects were asked if they were tired and if they felt cybersickness after each trial. If a subject reported feeling cybersickness three trials in a row, their testing was terminated as my goal was not to cause subjects discomfort. Additionally, apt completion of

Figure 6.3: The three motion profiles used in Specific Aim One.



the psychophysical task may become more difficult or impossible when experiencing cybersickness. 3 subjects did not complete testing because of cybersickness. Subjects were able to take a break (and remove the HMD) at any point during testing, most did so at least once during the testing session.

6.2.4 Data Processing

As noted earlier, to calculate inferred angular velocity perception, I computed the time between each button press and divided 90 degrees by that time period. This gave an average angular velocity perception for the time period between each button press. I computed an average angular velocity perception at each timestep (50Hz) for the duration of the motion profile to get an average inferred angular velocity perception and standard error across all subjects shown in Figure 6.4.

Approximately half our data had subjects rotate in the opposite direction for the same motion profile. Where a subject had experienced the motion profile in the opposite direction from baseline, I inverted the perceived rotation direction. Qualitatively, I did not identify substantial differences in perceived angular velocity based on the direction the subject had experienced the motion profile in.

6.3 Experimental Results

6.3.1 Results

Mean perception at the beginning and end of each test condition is consistent with data in the respective control condition. As expected, when test conditions that started with (without) visual cues, orientation perception at the beginning of the profile is consistent with the pattern seen in the with (without) visual cue test condition. Similarly, when test conditions ended with (without) visual cues, orientation perception at the end of the profile is consistent with orientation perception in the with (without) visual cues control condition.

Figure 6.5 shows full data (both control conditions and one test condition) for one motion

Figure 6.4: Each individual subject's inferred angular velocity perception.

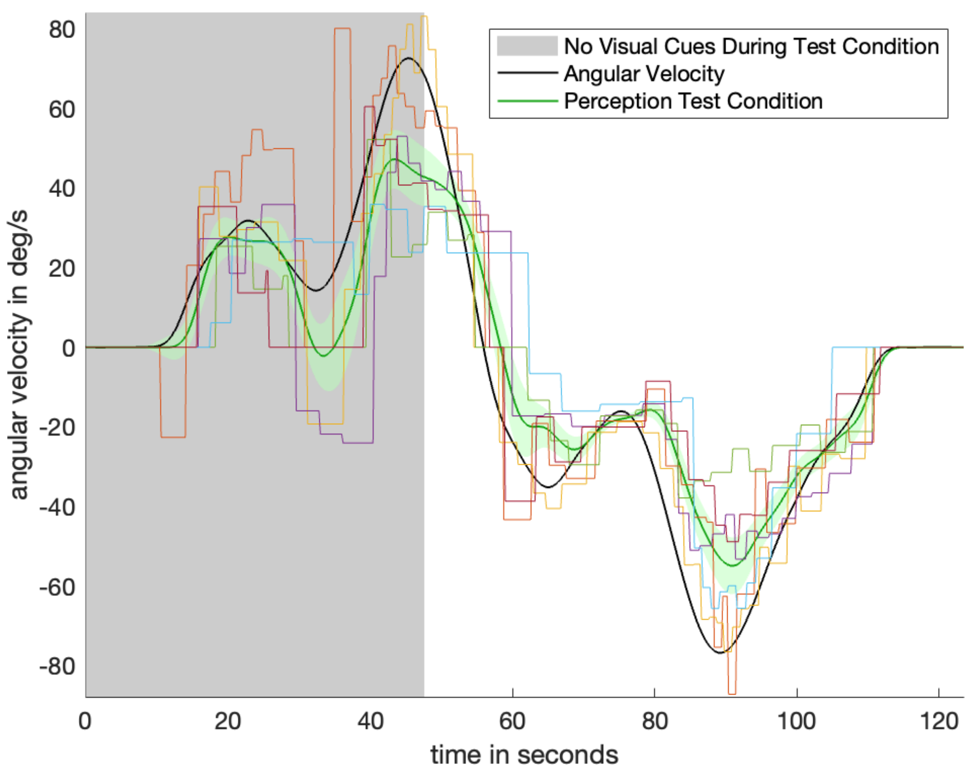
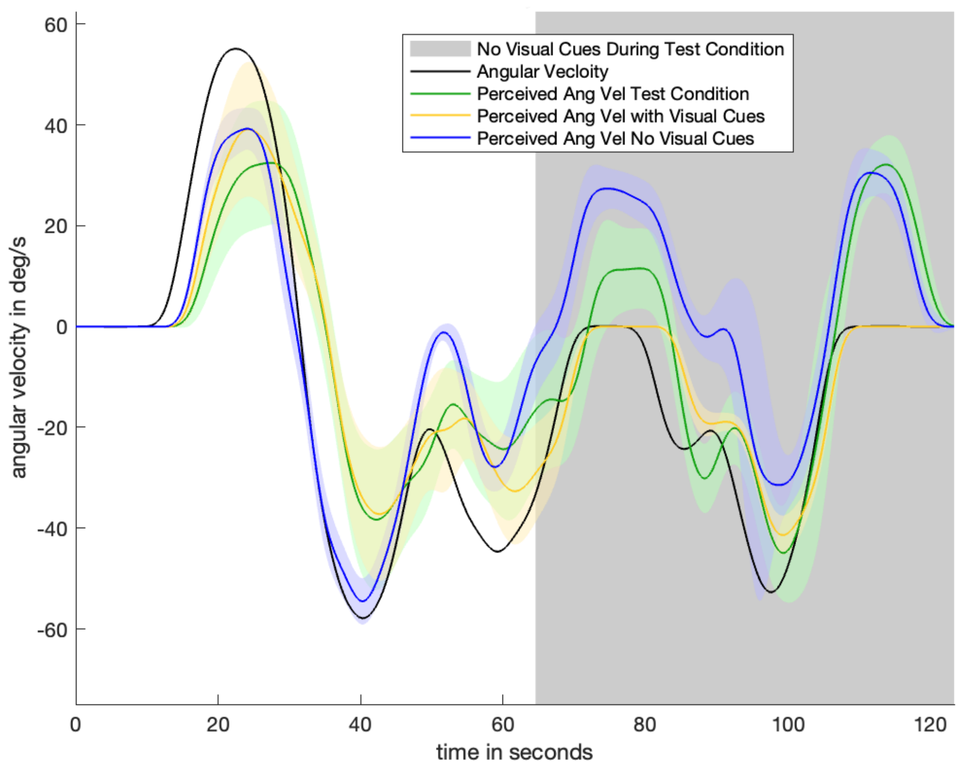


Figure 6.5: Data for one motion profile-test condition combination. The with (without) visual cues control conditions for that motion profile are shown in yellow (navy). Green is average orientation perception for the test condition.

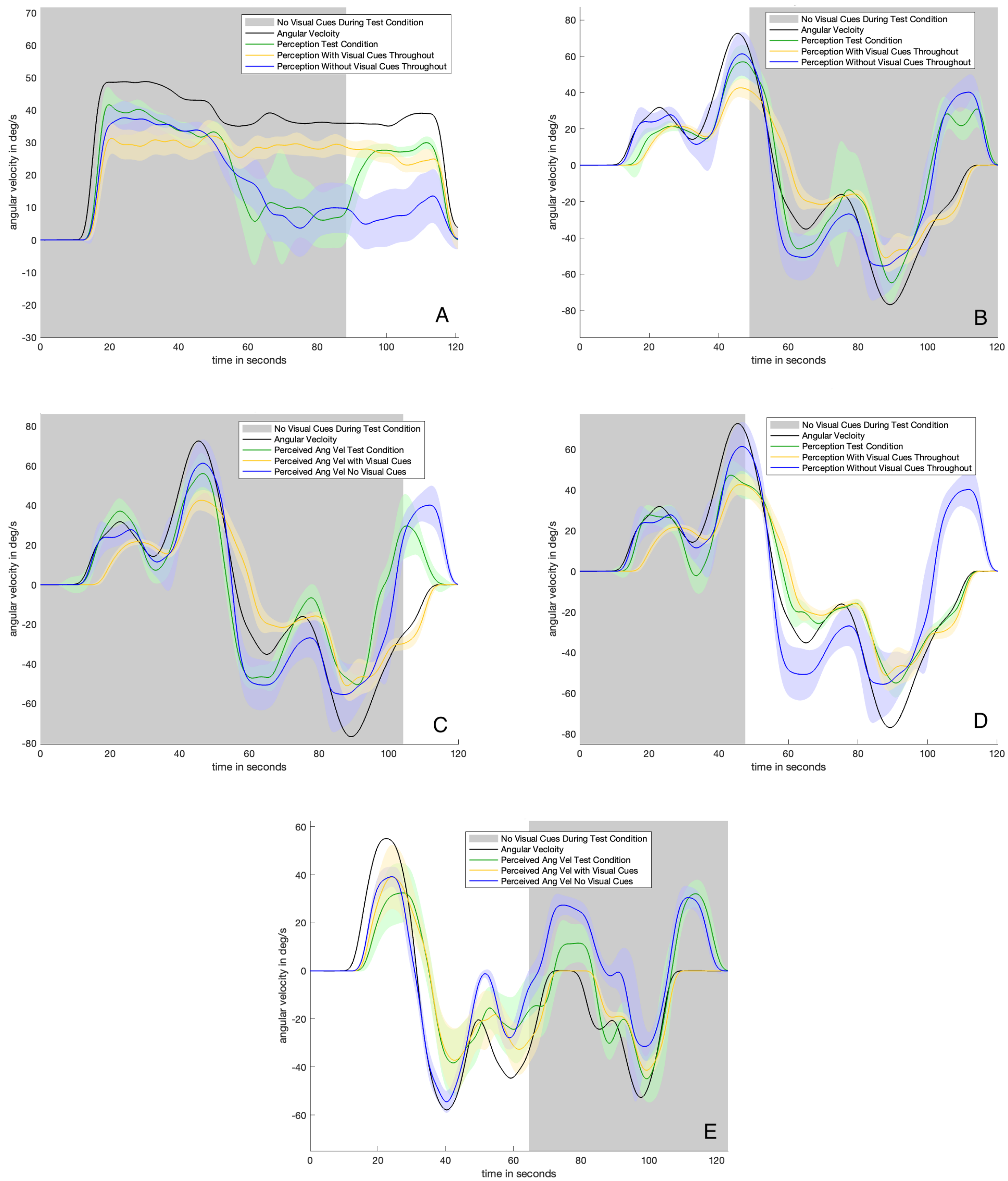


profile-test condition combination. Notably, average perception during the test condition (green) begins by closely tracking the "with visual cues" control condition (yellow). After the visual cues are suddenly removed (grey), perception during the test condition (green) transitions to tracking the "no visual cues" control condition (navy). In the data shown in Figure 6.5, there appears to be a 30 second transitionary period between removal of visual cues and the test condition becoming similar to (and within the standard error bounds of) the second control condition.

Figure 6.6 displays the perceptual data in the remaining motion profiles and visual transitions (not captured in Figure 6.5). The top four panels show the sudden appearance of visual cues. Qualitatively examining each plot, there appears to be a transition period of around ten seconds: it takes around ten seconds for the test condition (green) line to transition from following the no visual cues condition (navy) line to following the with visual cues (yellow) line. The bottom plot of Figure 6.6 and the plot in Figure 6.5 show about a 30 second transition period in the opposite direction (where visual cues are suddenly removed). Figure 6.5 shows that the impact of velocity storage resulting in sensation of motion in the opposite direction after one has become stationary is muted. Notably, both a 10 second and 30 second delay are longer than the delay expected to be associated with the psychophysical perceptual task. With a button press every 90 degrees and subjects rotating around 40 degrees per second, it would take less than 3 seconds ($\frac{90deg}{40deg/s} < 3s$) for perception to "jump" from a decayed state to tracking the actual motion (in the case of visual cues suddenly appearing) if the delay were only a matter of the psychophysical perceptual task.

Not all experimental data I collected has been presented in this thesis. I had initially collected data using motion profiles that ended up being predictable to most subjects. Although, based on existing literature on the vestibular system, I expected to see misperception of motion, many subjects were able to accurately perceive their motion even without visual cues. An example of this is shown in Figure 6.7. In the data shown Figure 6.7, there was no difference between the two control conditions. The test condition could then not transition between the two (there would be no change in pattern of motion perception before or after a transition in the availability of visual cues). Since data where there was not a substantial difference between the two control conditions was not

Figure 6.6: Plot matrix to show experimental data collected in Aim One.



useful for quantifying motion perception before and after a sudden transition in the availability of visual cues, I excluded those profiles from my analysis. All data collected (but not necessarily analysed) is shown in Appendix A.

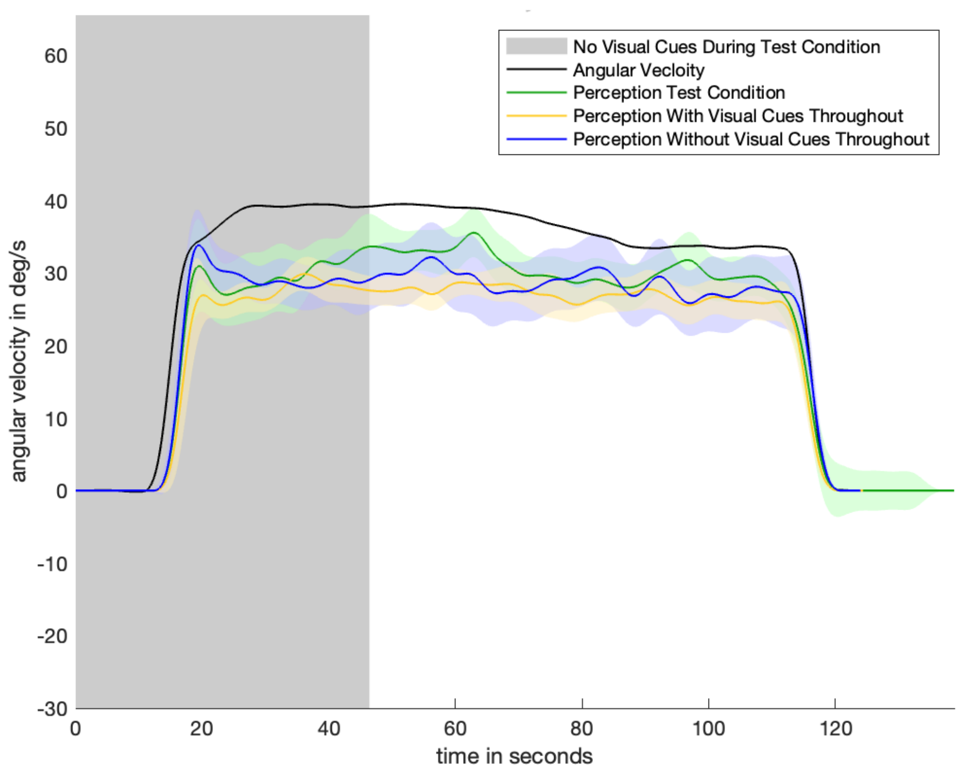
6.4 Modeling

The brain can be modeled as a black box that receives vestibular sensory information and visual cues and outputs a perception of orientation. The goal of the modelling process is to generate a computational model that mimics the output of the human brain. Based the different ways in which we are able to characterize our spatial orientation, the model must predict a perception of external state. While the model is capable of producing error terms (difference between expected and actual sensory signal), this is outside the scope of the observer model generally. The scope of the modelling process within this thesis is to have the model of perception accurately match true perception following a sudden change in visual cue availability. For Specific Aim One, therefore, the goal is to produce a model in which predicted angular velocity perception is consistent with measured angular velocity perception during Earth-vertical yaw motion.

6.4.1 Fundamental Model Changes

Based on the slow integration of new visual information seen in the sudden appearance of visual cues, I hypothesized that low pass filtering may exist in the brain's processing of visual pathways. The only change I made to the Newman, 2009 model was to add a low pass filter to the visual angular velocity cue pathway, shown in Figure 6.8. I hypothesize that the filtering occurs after sensory input has been compared to expected sensory input (the error term of the sensory conflict model is filtered) rather than the direct sensory input itself. This is because we propose that filtering occurs within the central nervous system (CNS) processing block of the model. The placement of the new low pass filter shown in Figure 6.8 indicates that the human is gradually integrating these visual cues that greatly differ from expectation as opposed to gradually integrating any change in visual angular rotation cues (which would be what a filter placed outside

Figure 6.7: One of the motion profiles and corresponding data that was excluded from the analysis.



the CNS block might describe).

6.4.2 Model Parameter Tuning Methods

The model parameters are gains (denoted k_i) and a filter time constant (denoted $\tau_{\omega v}$). These parameters define model behaviour and must be tuned to fit experimental data. Merfeld, 1993 chose gains and time constants that produced model outputs which qualitatively mimicked eye movement responses observed empirically. Newman, 2009 used parameters identified by Vingerhoets, 2007 fit to perceptual reports during an off-vertical axis motion paradigm. Vingerhoets, 2007 used a quantitative method but only tested 6 potential parameters values for model gains [Vingerhoets et al., 2007]. Notably, Vingerhoets, 2007 found the largest tested value of k_ω to best fit their data but did not test any higher values.

To be more rigorous, I was able to quantitatively optimize model parameters over a bounded space. I therefore chose to tune the gain value of k_ω (the gain of the vestibular angular velocity pathway) in addition to the time constant, $\tau_{\omega v}$, of the low pass filter I added.

In order to quantitatively tune k_ω, I generated an observer prediction for each motion profile without visual cues throughout the motion profile (control condition). I calculated the root mean squared error (RMSE, shown in Equation 6.1) between the observer prediction and the average reported perception in our dataset. I then ran this through an optimization algorithm [MatLab, 2006] set to minimize RMSE by changing k_ω. Notably, since I was simulating observer without visual cues, the prediction would not be impacted by the new low pass filter I added.

I found that across my experimental data, optimal $k_\omega = 25$.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \hat{x}_i)^2}{N}} \tag{6.1}$$

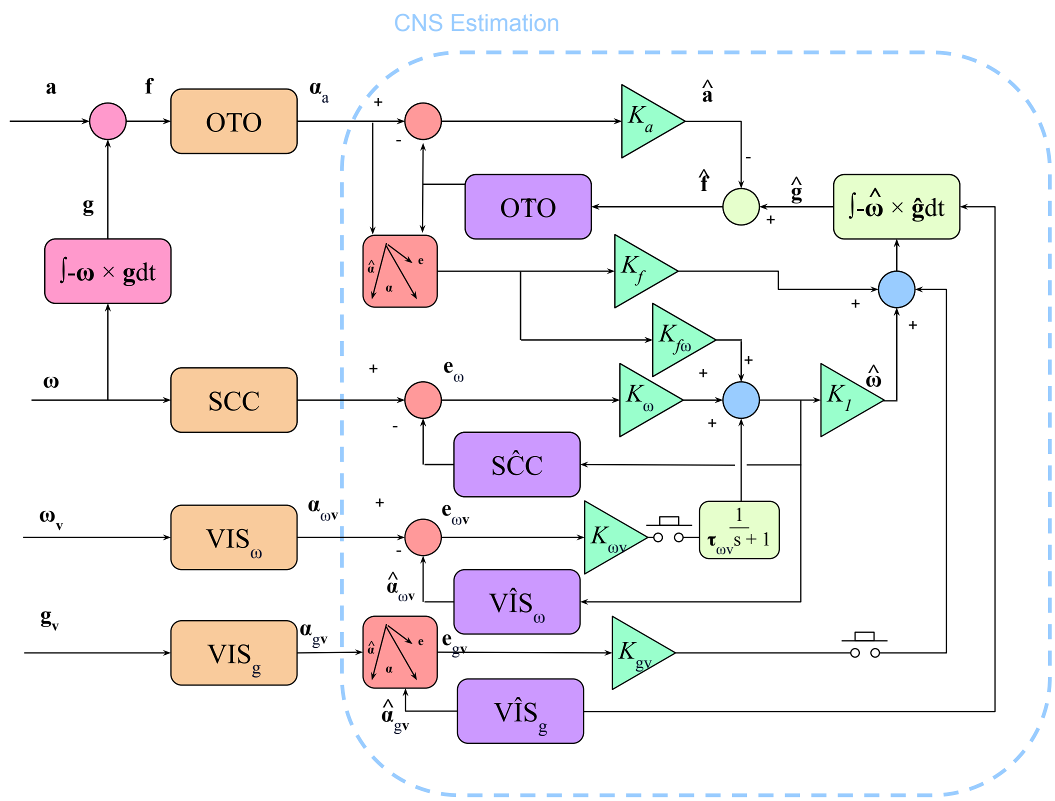
Where:

x_i - perceived angular velocity at each discretized time step

$\hat{x}_i$ - predicted angular velocity at each discretized time step

N - total number of time steps in discretized simulation

Figure 6.8: Updated Observer model with low pass filtering in the visual angular velocity pathway.



I employed the same strategy to compute an optimal value of $\tau_{\omega v}$. I set $k_\omega = k_{\omega v} = 25$. Using K_{wv} of similar magnitude to K_w yielded reasonable predicted perception of angular velocity as those empirically observed during the control condition with visual cues available throughout the trial. I ran the same optimization process on all but two test conditions of my experimental data to compute the best fitting value of $\tau_{\omega v}$. I purposefully excluded two test conditions (one a sudden loss of visual cue availability, one a sudden gain) to later compare the tuned model to experimental data that was explicitly not used in the tuning process.

The optimization process returned a value of $\tau_{\omega v} = 5.0$ seconds.

6.4.3 Model Predictions as Compared to Experimental Data

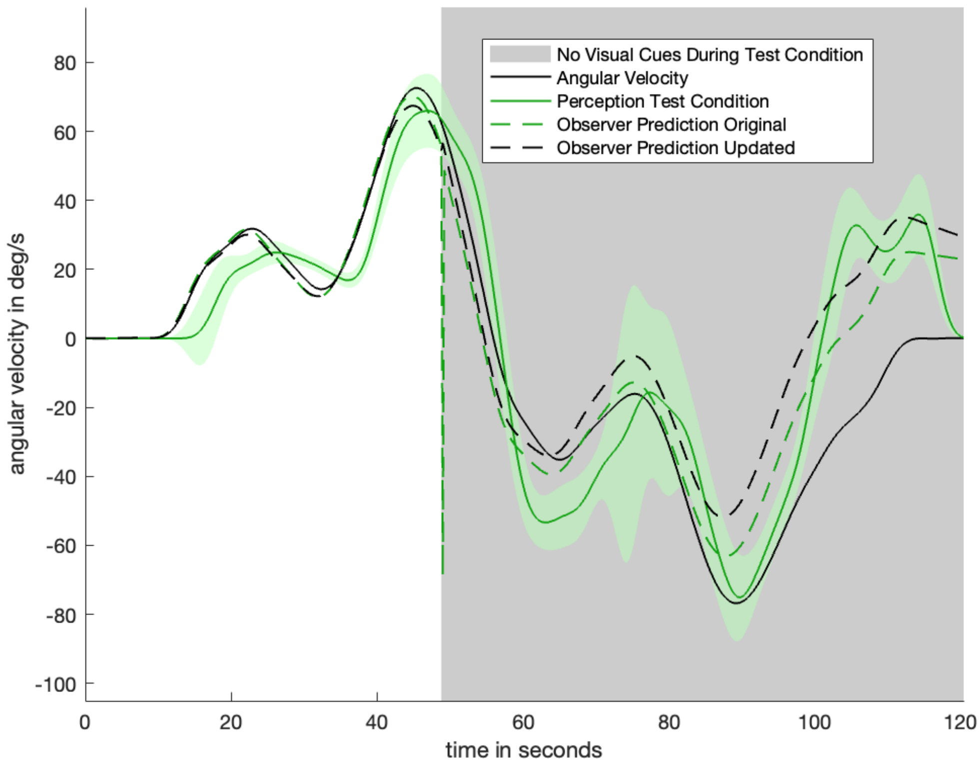
Updated model predictions qualitatively fit the data of the unseen test cases as shown in Figure 6.9. In both "test" cases presented in Figure 6.9, the updated model no longer shows a discontinuity in predicted perception of angular velocity immediately following the visual transition. In the case of visual cues suddenly appearing (Figure 6.9, bottom plot), the updated model shows a continuous, gradual transition from perceiving low or no angular velocity to an accurate perception within around ten seconds.

Updated model predictions also fit the test cases that were used to tune the parameters. Figure 6.10 shows original and updated model predictions for the remaining test cases. Again, we see that the discontinuity at the visual transition has been resolved via the addition of low pass filtering.

Since the low pass filtering was added to a visual perceptual pathway of the model, the model prediction in the absence of visual cues will remain unchanged. To verify that the addition of filtering did not disrupt perception predictions when visual angular velocity cues are present, I ran the original model and updated model on the control condition where visual cues were available for the entire motion. As shown in Figure 6.11, the updated model is not substantially different from the original model when visual cues are available the entire time.

A caveat to my quantitative modelling approach is that it required the adjustment of a

Figure 6.9: Updated model prediction against Newman, 2009 model prediction.



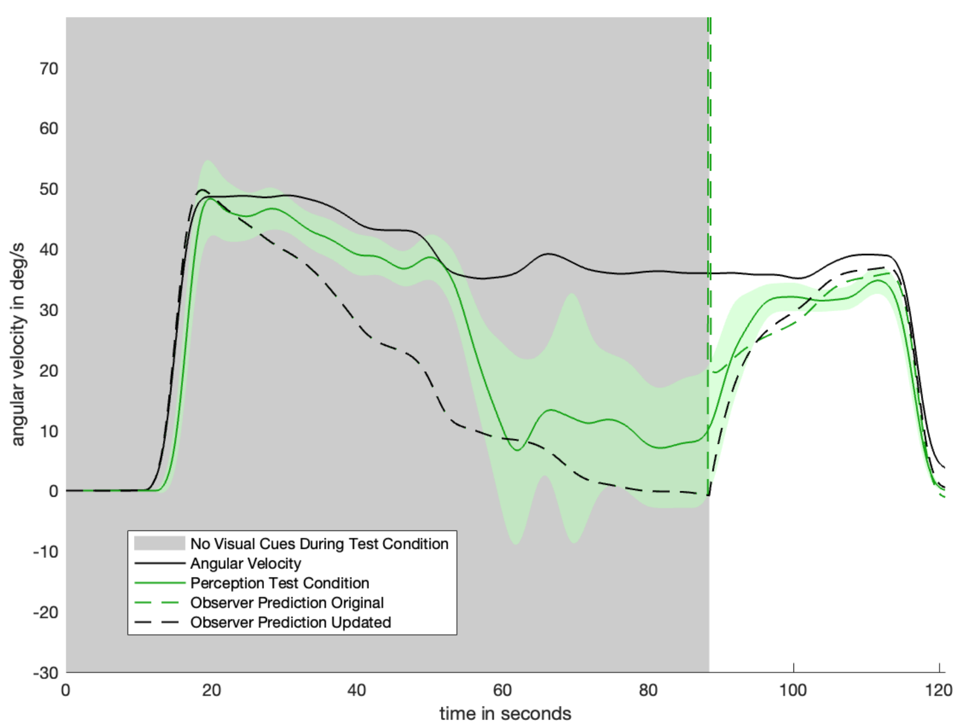


Figure 6.10: Updated model (dashed black) predictions and original model (dashed green) predictions.

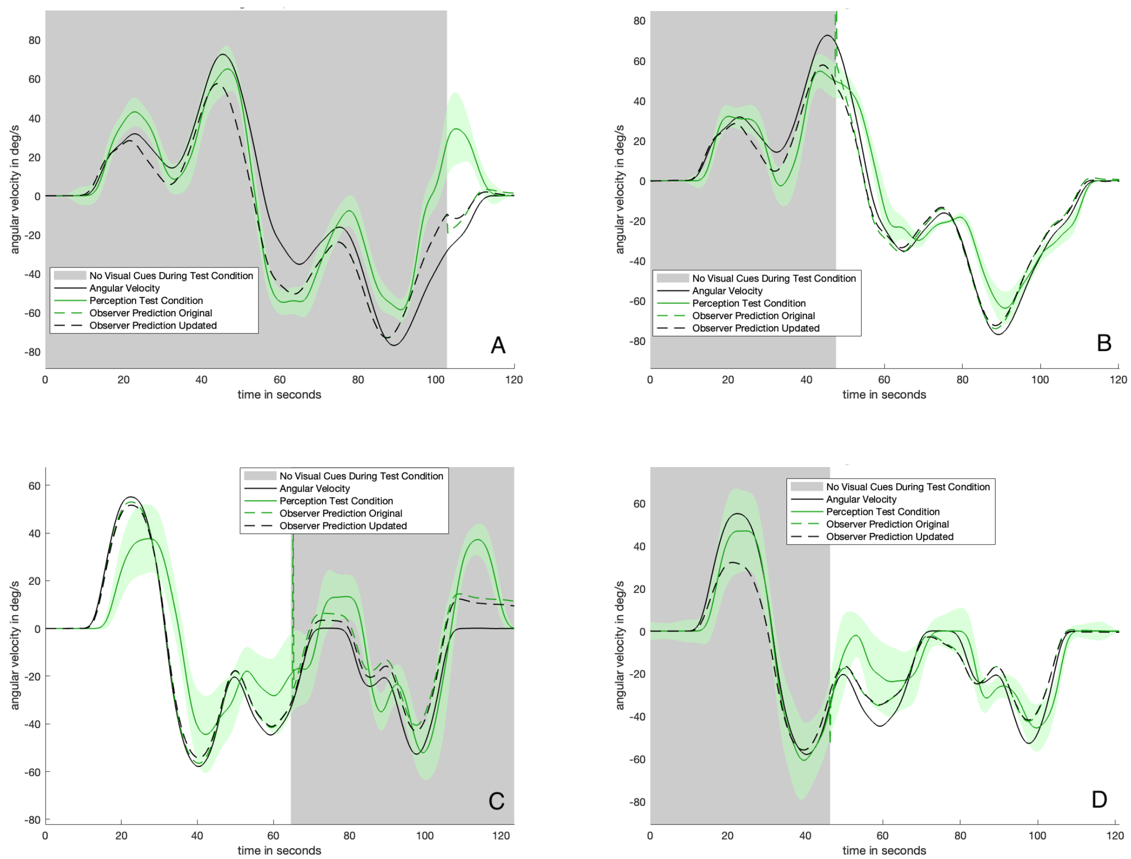
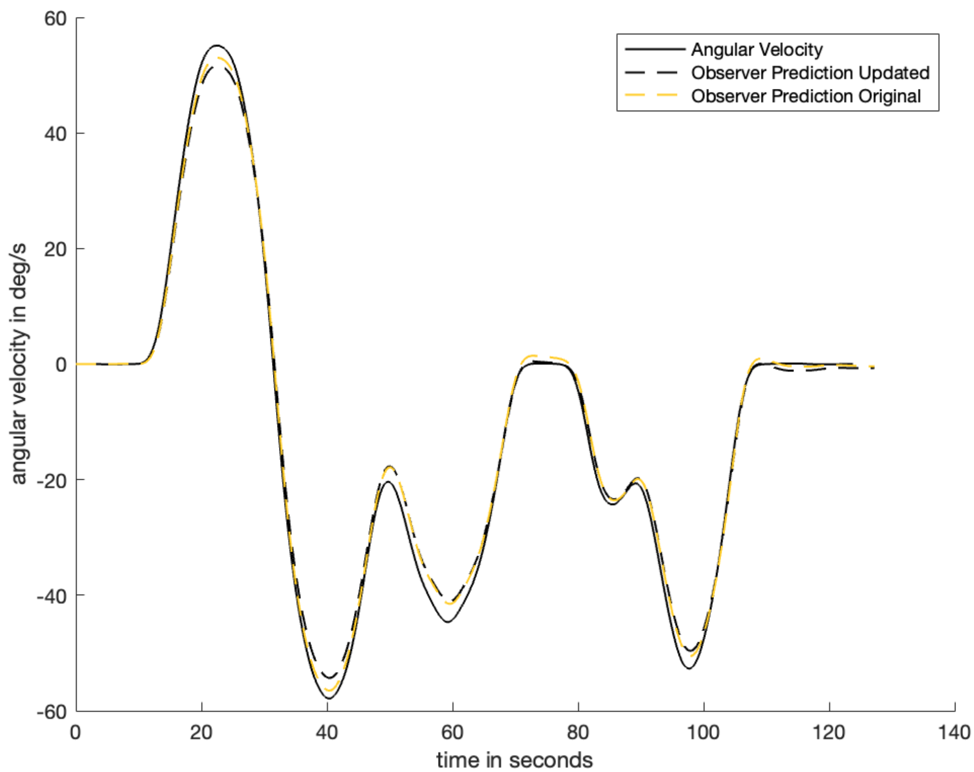


Figure 6.11: Updated model prediction against Newman, 2009 model prediction.



nuisance parameter (f_{scc}) that exists within the current *Simulink* implementation of the Observer model. f_{scc} was set to 2 by Newman, 2009 to keep simulations stable. Increasing the visual angular velocity gain will push the simulation unstable (and produce an oscillating prediction of perception). Lowering f_{scc} can resolve this instability. When I ran my initial optimization process, my optimization algorithm reliably returned the maximum value of $k_\omega = 12.1$ without the simulation going unstable. Running the optimization process with $k_\omega = 12.1$ returned a value of $\tau_{\omega v} = 5.3$ seconds. Saliently, computing $\tau_{\omega v}$ with different nuisance parameters $(k_\omega, k_{\omega v})$ does not substantially change the value that $\tau_{\omega v}$ converges on.

6.5 Discussion and Conclusions

The modelling aspect of Aim One went from updating an existing model to a quantitative multivariate parametrization process. However, the fitting of $\tau_{\omega v}$ was robust to manipulations of the nuisance parameters $(k_\omega, k_{\omega v})$ discussed above.

A notable limitation of Aim One is the use of virtual reality for presenting visual orientation cues. Current literature comparing virtual orientation cues to physical cues is sparse. Existing literature indicates that virtual visual cues are sufficient for angular motion [Pretto et al., 2009]. However, other studies [Ivanenko et al., 1998] [Kimura et al., 2017] have shown that virtual cues may not be analogous to physical cues.

A second aspect to note is the highly variable nature of subject responses, particularly in the absence of any visual cues. The current model architecture predicts an average perceived perception and does not support or capture how variable the predicted perception can be.

A final limitation is the size of the study and the fact that many subjects did not complete every test condition. Each condition presented in this thesis contains perceptual data from at least 6 subjects because it was possible to capture perceptual dynamics across different conditions with relatively few subjects. However, a larger dataset could be helpful in reducing the uncertainty of measured perception especially where visual cues were not present. Importantly for the overarching goal of this work, study participants were selected to be ordinarily healthy individuals and the subject pool is broadly representative of the high-performance pilot population with regards to healthy visual and vestibular sensing.

6.6 Summary

In Specific Aim One, I have quantified orientation perception during sudden transitions in the availability of visual cues. I have presented a new model of orientation perception that is robust to sudden changes in visual cues during angular motion. The new model of orientation perception provides a predicted orientation perception that is consistent with the experimental data collected in the first part of Specific Aim One. The new model of orientation perception is consistent with experimental data that was explicitly not used to train the model. The changes I have made to the model do not substantially change its predictions for previously verified dynamic scenarios (e.g., visual cues available the entire time).

Chapter 7

Specific Aim Two

7.1 Introduction

I measured roll tilt perception during motions that contained both linear translation (Earth-horizontal to the subject's left-right) and roll tilt. I chose roll tilt coupled with left-right translation because there is an existing, well verified psychophysical task for collecting roll tilt perception data. There is less consensus on how to accurately measure orientation perception during pitch tilt motion. Low frequency translation can induce spurious sensations of tilt. These misperceptions of tilt at frequencies close to 0.2Hz are due to the high pass filter like characteristics of the semicircular canal resulting in difficultly disambiguating otolith and semicircular canal cues. At higher frequencies, afference from the semicircular canals facilitates disambiguating tilt from translation [Merfeld et al., 2005].

7.2 Experimental Methods

Subjects were seated in the *Tilt Translation Sled* (TTS) (see Figure 7.1) and secured with a five-point harness. Subjects experienced motions containing roll tilt. During the motions, subjects were tasked with constantly reporting their perception of roll tilt position (the extent to which they had been tilted and not the speed or acceleration to which they were being rotated). Subjects were wearing a VR headset (HMD) *(HTC, New Taipei City, Taiwan)* for the delivery of visual cues.

Subjects reported their sensation of roll motion by holding a haptic bar level (relative to earth horizontal) as they moved. The task of holding a haptic bar steady is extensively used in previous

Figure 7.1: Photograph to show Tilt Translation Sled (TTS) and track (fisheye lens).

literature and well validated as a measure of roll tilt perception [Barnett-Cowan and Harris, 2008] [Clark et al., 2015a] [Merfeld et al., 2001] [Park et al., 2006] [Rader et al., 2009] [Voros and Clark, 2023] [Wade and Curthoys, 1997] [Zupan and Merfeld, 2003]. Due to physical limitations of the motion device (the TTS), I was not able to reverse the direction of motion for some subjects like I had done in Aim One. Instead, to account for left right tilt perception differences, motions used in Aim Two were designed to be bidirectional and, in two of the three cases, symmetrical (with regards to left/right tilt motion).

White noise was provided via headphones for the duration of testing in order to reduce auditory cues from the motors of the motion device.

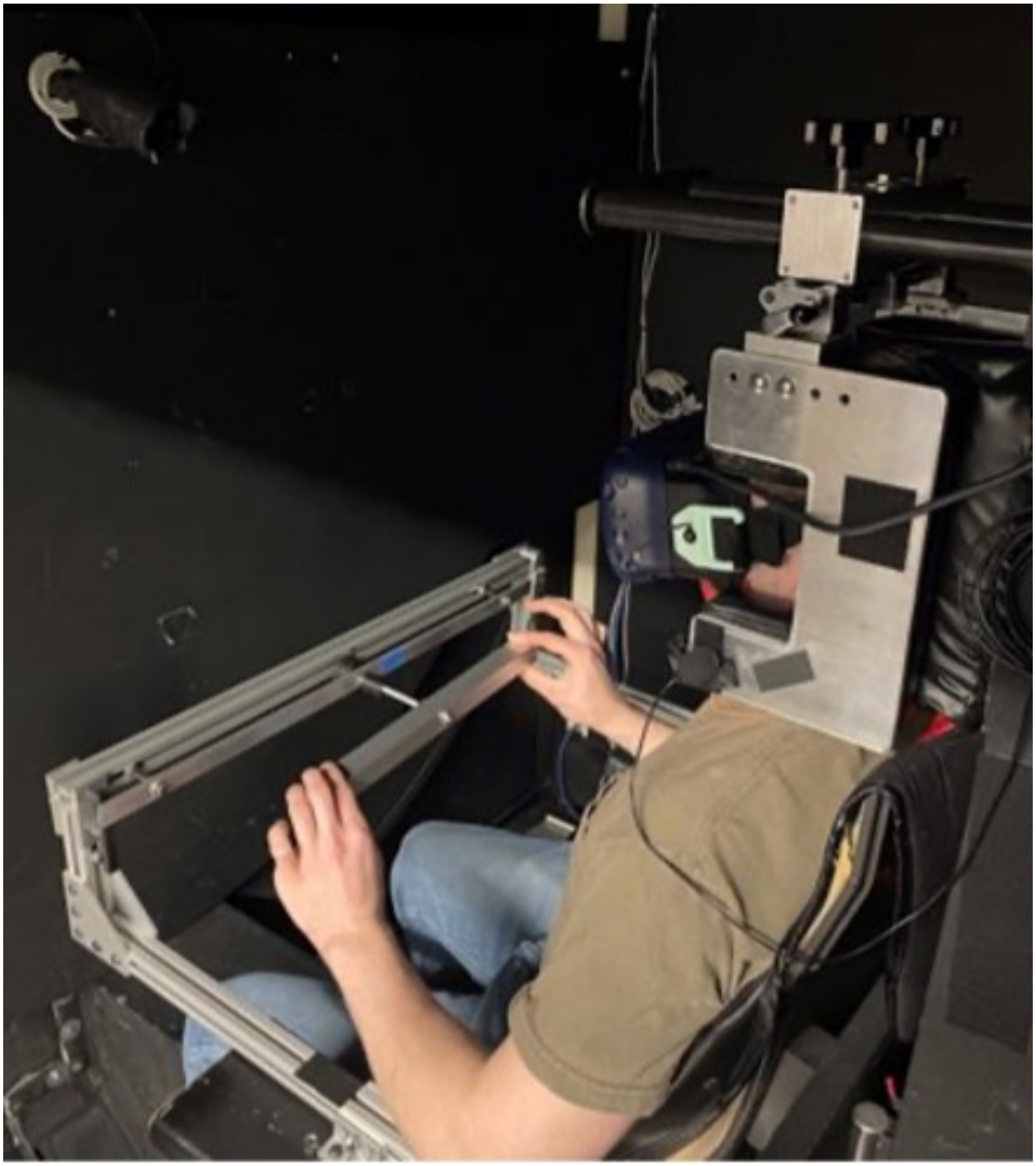
7.2.1 Experimental Design

Exclusion criteria were any known issues of vestibular dysfunction (self-reported), a Motion Sickness Simulator Questionnaire score above the 90th percentile, age below 18 or over 40 or requiring glasses for 20/20 vision. Data was collected from 12 unique subjects (6 female; mean age 22 SD $\pm$ 3 years; 8 white, 2 Asian, and 2 more than one race).

The test condition trials contained both roll and translation motions designed to induce a misperception of tilt. Some of the combined roll tilt and translation motions were designed to cancel utricular shear and others were designed to amplify it. I used 3 different motion profiles: one that cancelled interaural shear (see Figure 7.4), one that doubled it and one that left net gravitational inertial to one side. Subjects reported their sensation of roll tilt continuously. In addition to the 3 test profiles, I used four practice trails and three bias-control trials. The bias-control trials consisted of tilt motion only and were completed with three distinct types of visual cues. The bias-control trials were designed to provide gravito-inertial stimulation that was consistent with actual roll tilt motion and thus were expected to yield accurate tilt perception in subjects.

The visual scene provided was designed to be a simplification of naturalistic visual cues (Figure 7.3). Subjects were provided a horizon and dot pattern that was infinitely far away. The visual scene was designed to be similar to clouds and horizon that a pilot may see while flying.

Figure 7.2: Photograph to show the haptic horizontal bar situated within the cab of the Tilt Translation Sled. Subjects were seated in the chair, wore a VR headset and were instructed to hold the haptic bar level as they tilted. Subjects were instructed to hold the bar between thumb and forefinger.



With the scene infinitely far away, the scene will roll as the subject engages in roll tilt motion but will not visibly translate if the subject translates left or right.

7.2.2 Test Procedure

Subjects first completed four practice trials to familiarize themselves with the psychophysical task, the visual scenes, and the types of motions that might be experienced. All subjects had the option of more practice trials, but none obliged. Once practice trials were complete, subjects completed the full course of testing. Subjects typically completed testing in a single, two hour long, session without breaks. One subject was removed due to inability to understand and reasonably perform the psychophysical task.

7.2.3 Motion Profiles

I used three unique motion profiles under different visual cue conditions. Translation was used to both cancel (see Figure 7.4) and double interaural shear due to tilt. The combinations of tilt and translation were designed to be difficult for subjects to disambiguate when perceiving tilt. In order to cancel out interaural shear, the device needed to linearly accelerate in the corresponding lateral direction. The length of the TTS track length (6.25 meters) limited how large tilt motions could be during a shear cancelling motion profile. The tilts were designed to be large enough such that they were perceptible but small enough such that the cancelling translation profile fit within the TTS track. The motions also had to be of low enough frequency such that both the haptic horizontal task remained feasible (extremely rapid tilts may not result in haptic task data matching true perception) and the coupled translations were likely to be misperceived as tilts. Due to motion device limitations, pure shear cancelling tilts did not exceed three degrees.

7.2.4 Data Processing

Due to hardware limitations, we were not able to "zero" the haptic bar at each trial. Therefore, for each trial, I computed the average haptic horizontal reported by the subject (via the haptic

Figure 7.3: Visual scene presented to subjects in Specific Aim Two. The dots provided a visual angular velocity cue. The horizon provided a horizontality cue. The dots did not translate left or right even if the subject was translating. The scene was designed to mimic objects that are infinitely far away, such as clouds.

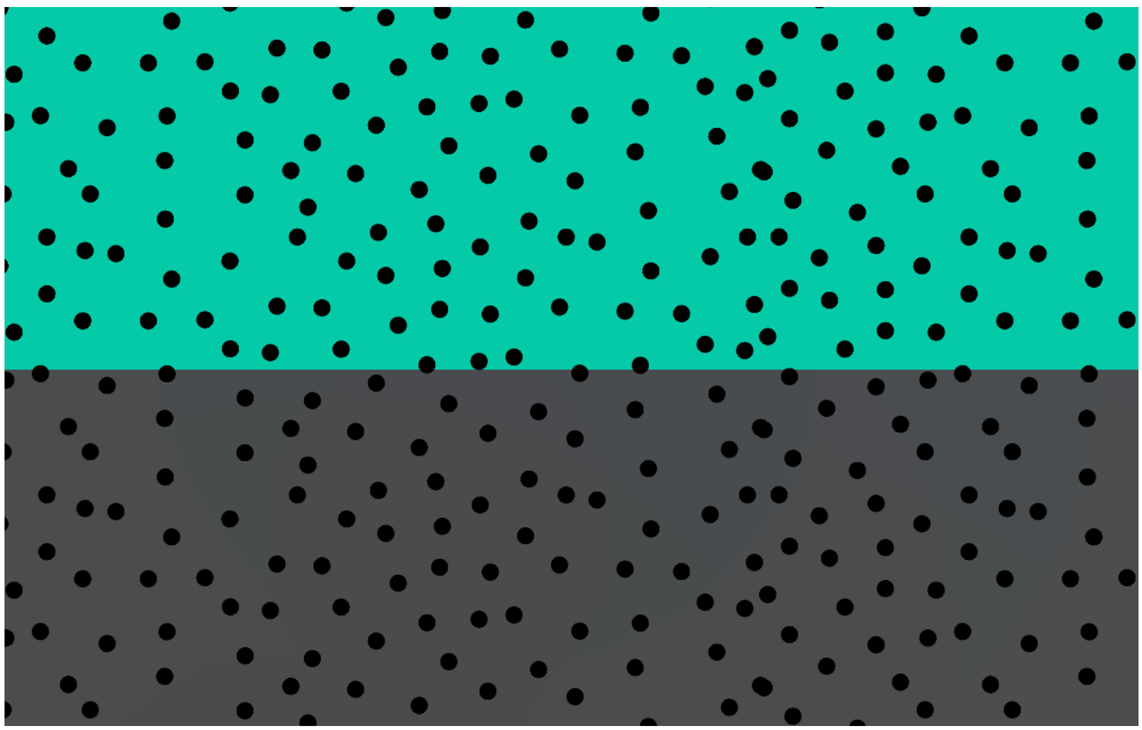
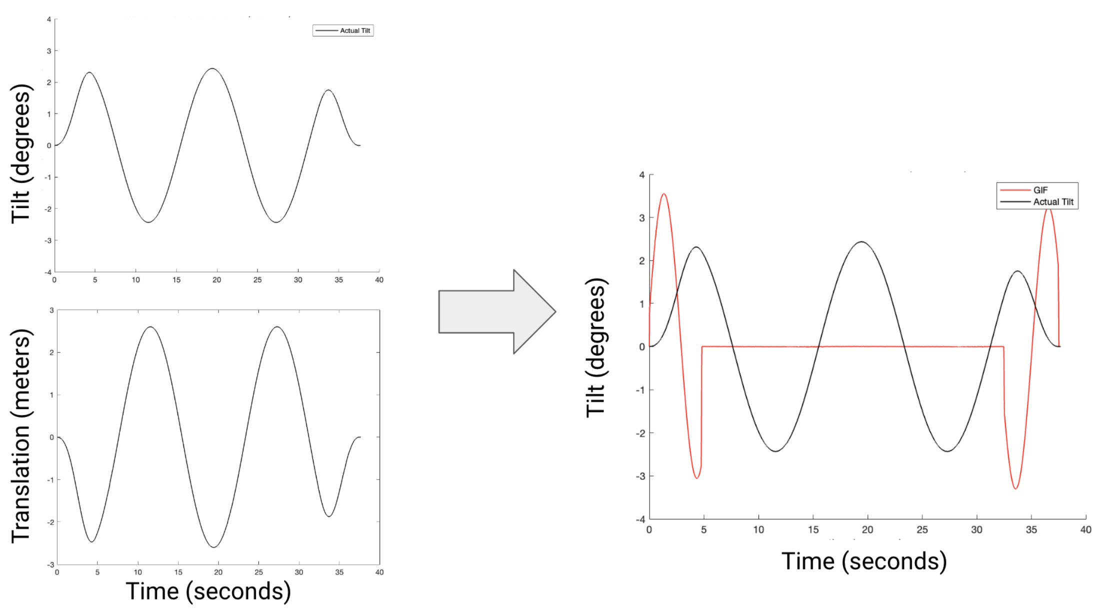


Figure 7.4: The shear cancelling profile used a combination of tilt and translation to cancel utricular shear (GIF) (shown in red, right).



bar). I then adjusted the recorded haptic horizontal such that the average reported tilt was equal to the average tilt of the trial. (For example, a symmetric tilt profile would have average tilt of 0 degrees. If a subject's average tilt perception for that trial was 1 degree, I subtracted 1 degree from the recorded tilt at each discretized timestep.) I did this on a per-trial basis because the starting angle of the bar changed per trial and the offset of the hardware itself may drift during long testing sessions.

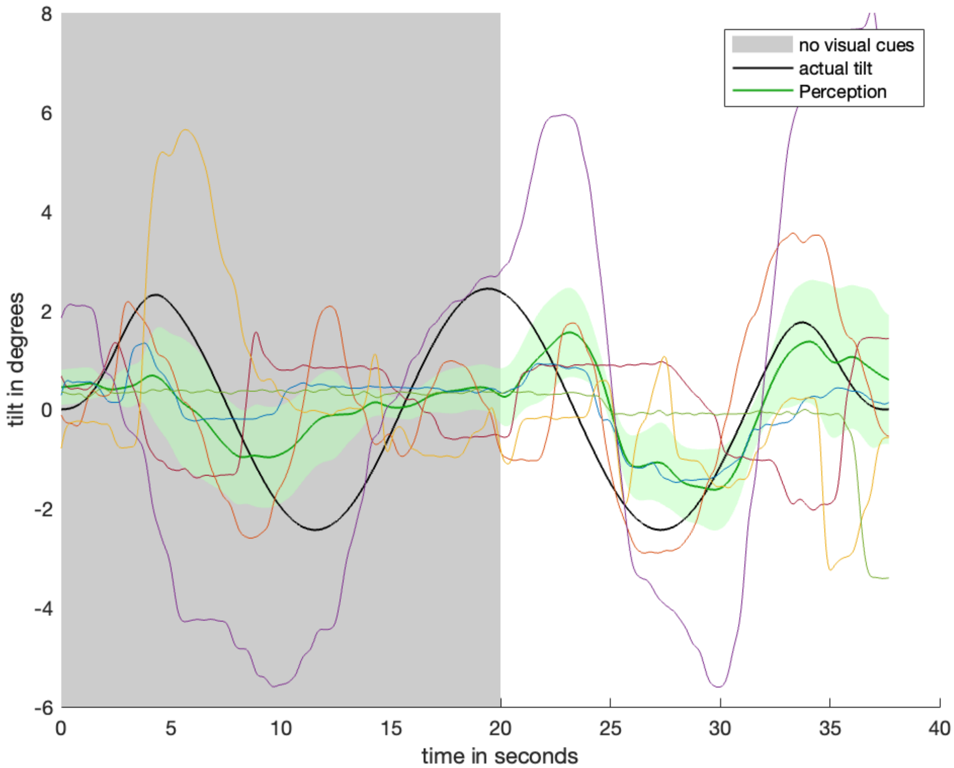
Next, to potentially adjust for scaling in the psychophysical task, I computed a scale factor for the subjective haptic horizontal reports. I used the bias-control trials (tilt only motions with visual cues) to determine the scale factor. With visual cues available and tilt motion only (i.e., no translation), I expected my subjects' tilt perception to near accurate. Therefore, with data from the bias-control trails, I was able to scale subjects' responses in order to account for the psychophysical task itself. Via the same optimization process used in Specific Aim One, I found a scale factor that was not substantially different from 1. Therefore, I chose not to scale subject data going forward.

Aggregate data is presented as an average at each discretized time step as well as the standard error surrounding the average perception. A visualization of individual subject responses and an average is shown in Figure 7.5.

7.3 Experimental Results

Results are presented as a single plot per "test condition." A "test condition" refers to a motion profile and visual cue availability condition (e.g., a shear cancelling profile where visual cues suddenly became available). Each plot (see Figure 7.4) contains information describing the motion profile in terms of true tilt (shown in black) and net gravitational inertial (shown in red). The net gravitational inertial (shown in red) was achieved via left-right translation. The exact translation profile is not directly shown in the results to avoid plot overcrowding; instead, only net gravitational inertial angle relative to the subject's body axis (red) is shown because it is the pertinent result of the lateral translation. When visual cues were not provided, I expected that tilt perception would be similar to net gravitational inertial angle (red). This is because the subject's

Figure 7.5: Individual subject perceptions (overlaid in single point lines) and average perception (green).



graviceptors (e.g., the otoliths) sense the net gravito-inertial and the angular velocity of the profiles was slow and small enough that the stimulation to the semicircular canals may not be able to disambiguate tilt and translation. The angular velocity and translation for the shear cancelling motion profile used in this thesis are shown in Figure 7.6. When visual cues were provided, I expected tilt perception to be accurate (similar to true tilt shown in black).

Without visual cues, subjects tended to report a perception of tilt that was consistent with net gravitational inertial and not true tilt. I expected this result due to the low frequency nature of the tilts subjects experienced. The test conditions show that when visual cues are provided (transition from grey to white background) subjects suddenly realize they have misperceived tilt and fairly rapidly update their tilt perception report (see Figure 7.7, 20-25 seconds).

The results in Specific Aim Two show a several seconds long integration of sudden visual cues in the scenario where visual cues are suddenly gained. In the opposite scenario (visual cues are suddenly removed), there is a tens of seconds long transitionary period whereby perception goes from following a "no visual cues perceptual pattern" to following a "with visual cues perceptual pattern."

Figure 7.8 details the remaining test conditions beyond the one shown in Figure 7.7. More data was collected but was deemed unhelpful for determining perceptual dynamics following a visual cue availability transition (see Appendix B). Taken in aggregate, the profiles in which the visual scene suddenly disappears (left side of Figure 7.8, panels A and C) there appears to be a transitionary period on the order of 5-8 seconds. In contrast, when the visual cues sudden become available (Figure 7.8 panels B and D) the transitionary period is substantially more rapid with the perceptual update happening in 1-4 seconds. This pattern of gradual integration of a new loss or gain of visual cues is qualitatively similar to the pattern seen in Specific Aim One but with shorter transitionary periods.

Figure 7.6: Full characterization of a shear cancelling profile that used a combination of tilt and translation.

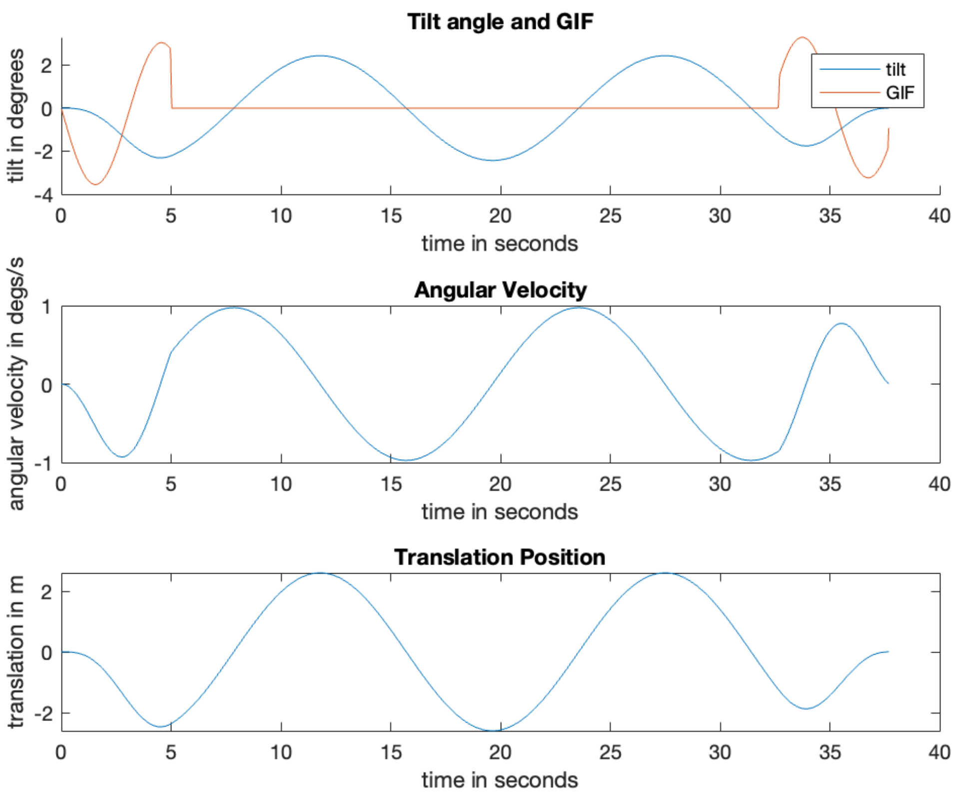


Figure 7.7: Tilt perception across the two control conditions (navy and yellow) in contrast to the test condition (green).

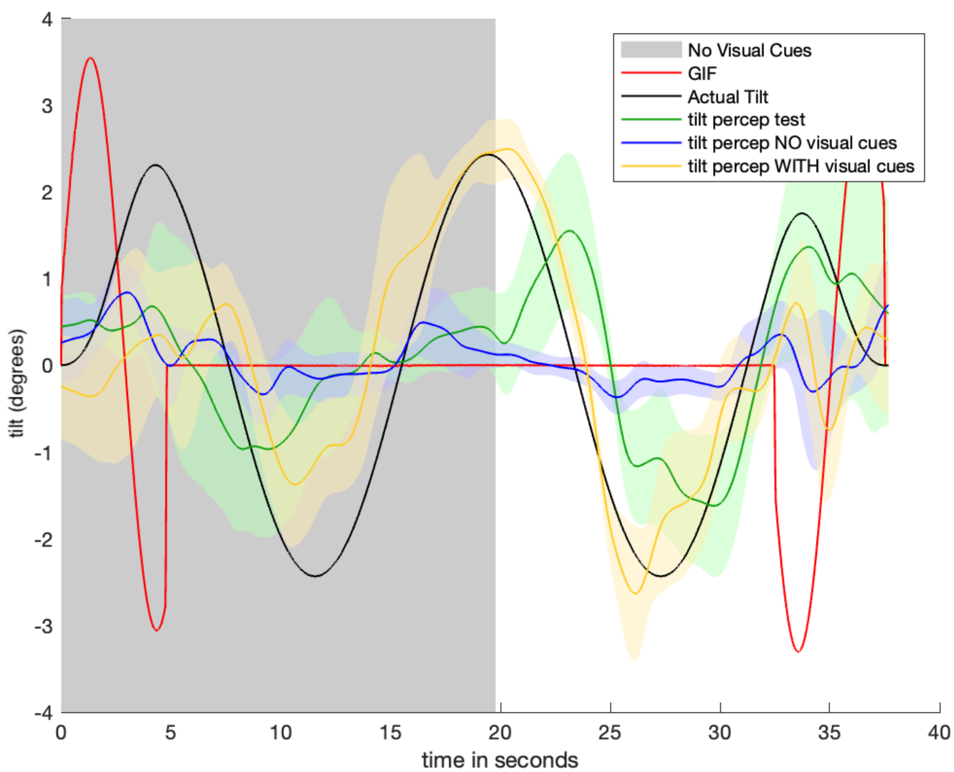
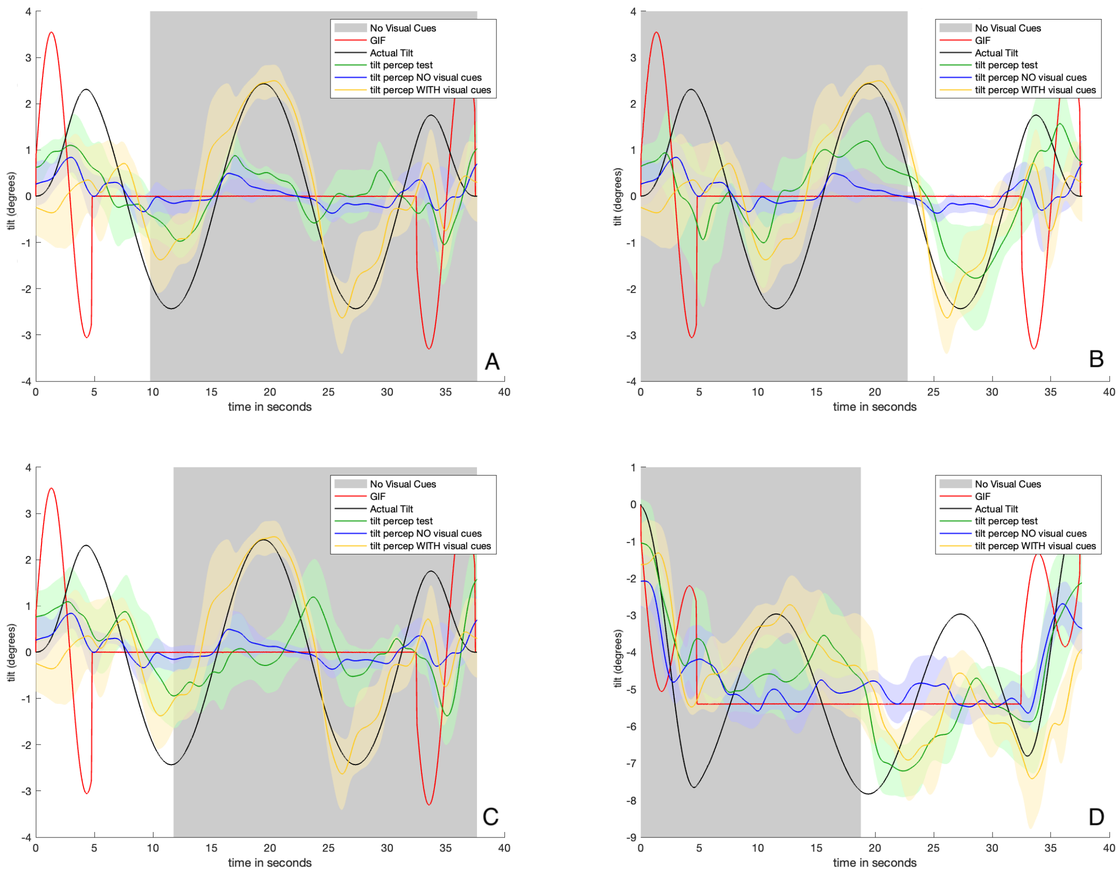


Figure 7.8: Suite of data collected and analysed in Specific Aim Two.



7.4 Modeling

The goal of the modeling process was to produce a model of roll tilt perception which was consistent with experimental findings in the first arm of Specific Aim Two. Based on aggregate subject data, there appears to be a time delay between sudden appearance of visual cues and a change in perception (see 20 – 25 seconds in Figure 7.7). However, based on individual subject responses, changes in tilt perception as measured by the haptic bar task appear more discontinuous on a per subject basis. This is shown in Figure 7.9.

Given that the model is designed to capture aggregate responses, I chose to alter the observer model to match aggregate subject data as opposed to capturing the discontinuous behaviour exhibited by some individual subjects. However, we emphasize that the aggregate response may be more gradual than exhibited by individual subjects and thus may slightly overestimate the duration of transitory dynamics following a transition in the availability of visual cues.

7.4.1 Fundamental Model Changes

In order to capture the dynamics of a gradual transition of perception over the course of two seconds in the scenario where visual cues suddenly appear, I opted to insert a low pass filter to the model. I hypothesized that the horizon presented to subjects in VR was a key component of tilt perception for this experiment. Therefore, I placed a low pass filter in the visual horizontality pathways of the existing [Newman, 2009] model. Shown in Figure 7.10, bottom right, is the additional low pass filter added to the observer model.

7.4.2 Model Parameter Tuning Methods

The addition of a low pass filter to the visual verticality pathway required setting a numerical value for the time constant, τ_{gv}, of the added filter. I employed a similar optimization method used in Specific Aim One to determine a value of τ_{gv}. In Specific Aim Two, I chose not to use train and test profiles because, unlike in Specific Aim One, Specific Aim Two only had five final test

Figure 7.9: Individual subject responses are shown in lighter point lines. Individual subject responses indicate a small time delay before rapidly updating their tilt perception as the visual scene suddenly becomes available.

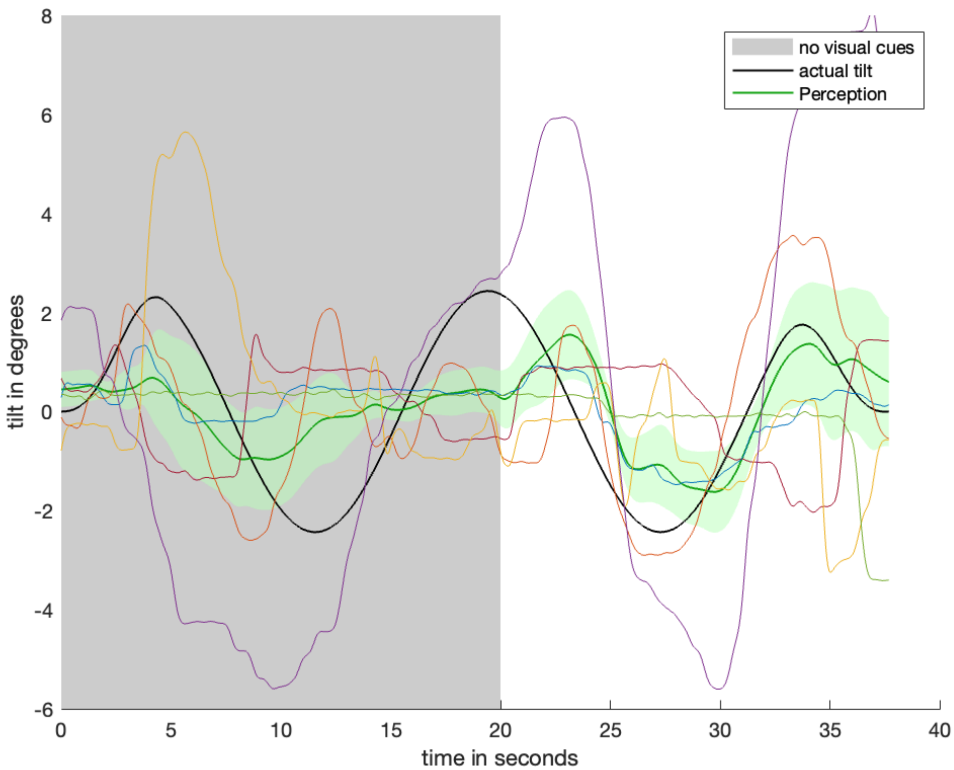
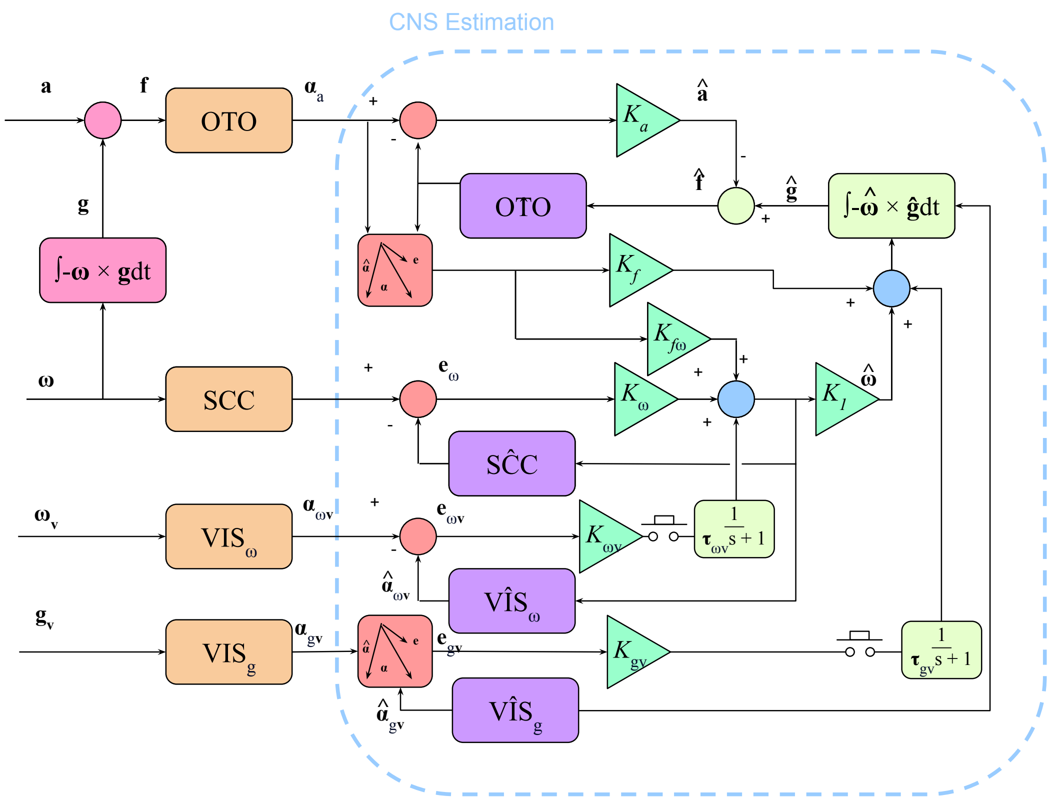


Figure 7.10: Updated observer model with low pass filtering in both the visual angular velocity and visual horizontality pathways.



conditions used for analysis. Among these test conditions, there were only two distinct motion profiles (the same motion profile had been used with different visual transition types and times). Therefore, I did not believe I had sufficient data to truly train and test the data. For example, the two "sudden loss of visual cues" test conditions (Figure 7.8, panels A and C) use the same underlying motion profile (with a different visual transition time). It would be disingenuous to train the model on the first, test on the second and claim that the model then made an accurate prediction on a wholly unseen motion.

Figure 7.11 shows RMSE for different values of τ_{gv} that were tested in the optimization process. There is a clear local minimum in RMSE surrounding a value of $\tau_{gv} = 1.2$ seconds. For the τ_{gv} process, I used the nuisance parameters presented by [Newman, 2009] which are different from some of the nuisance parameters computed in Specific Aim One. I used the observer model presented at the conclusion of Specific Aim One with the newly added low pass filter in the visual angular velocity pathway. Although I did not expect the visual angular velocity pathway to impact perception, I ensured that $\tau_{\omega v} = 5.0$ seconds, as optimized for in Specific Aim One. All experimental data collected in Specific Aim Two (presented in Figures 7.7 and 7.8) was used to compute τ_{gv}.

7.4.3 Model Predictions as Compared to Experimental Data

The addition of low pass filtering to the visual verticality pathway introduces a delay in tilt perception drastically changing following a visual cue availability transition (see Figure 7.12). The addition of low pass filtering also results in a slowed transition between perception following a "with visual cues" pattern to a "without visual cues pattern" shown bottom left in Figure 7.13.

While the updated model predictions appear relatively similar to those of the original model, the gradual change in perception (especially visible when visual cues suddenly become available) is better captured in the updated version of the model.

The addition of low pass filtering to a visual pathway means that the model predictions for motion profiles in which no visual cues were present will not change. The existing model was already able to robustly predict tilt perception under the influence of visual cues. Therefore, I wanted to

Figure 7.11: Filter time constant (τ_{gv}) against their root mean squared error (RMSE) between predicted perception (from model) and true perception (from experimental data).

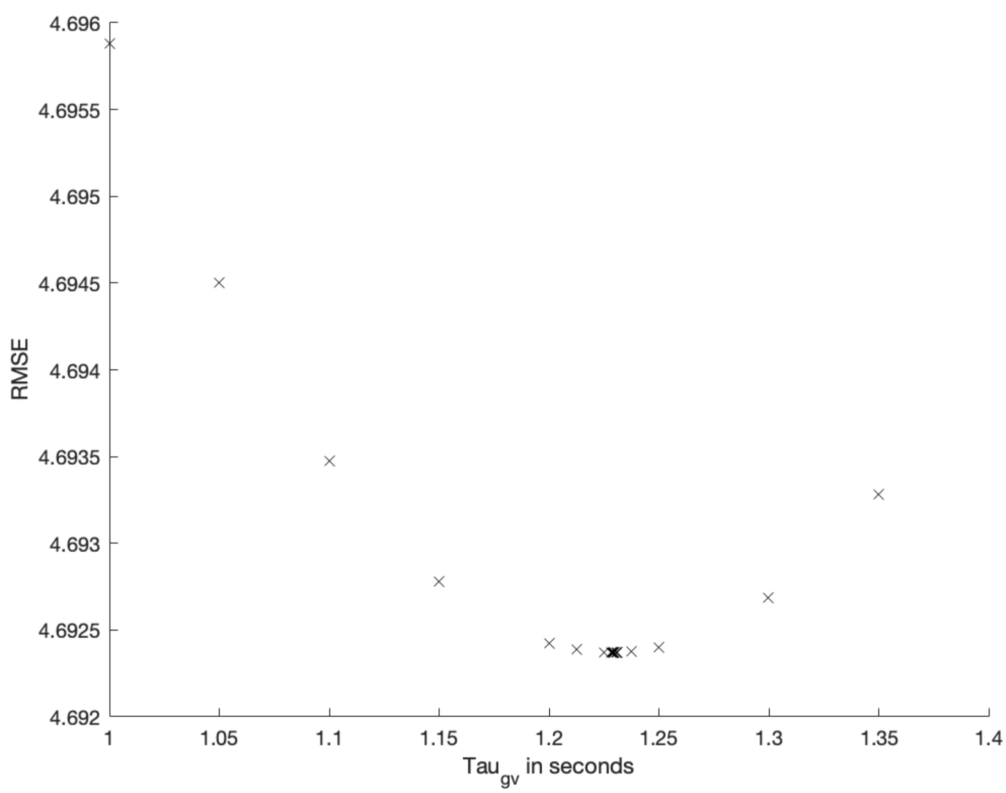


Figure 7.12: Comparison of Newman, 2009 model (dashed green) to the updated model (dashed black).

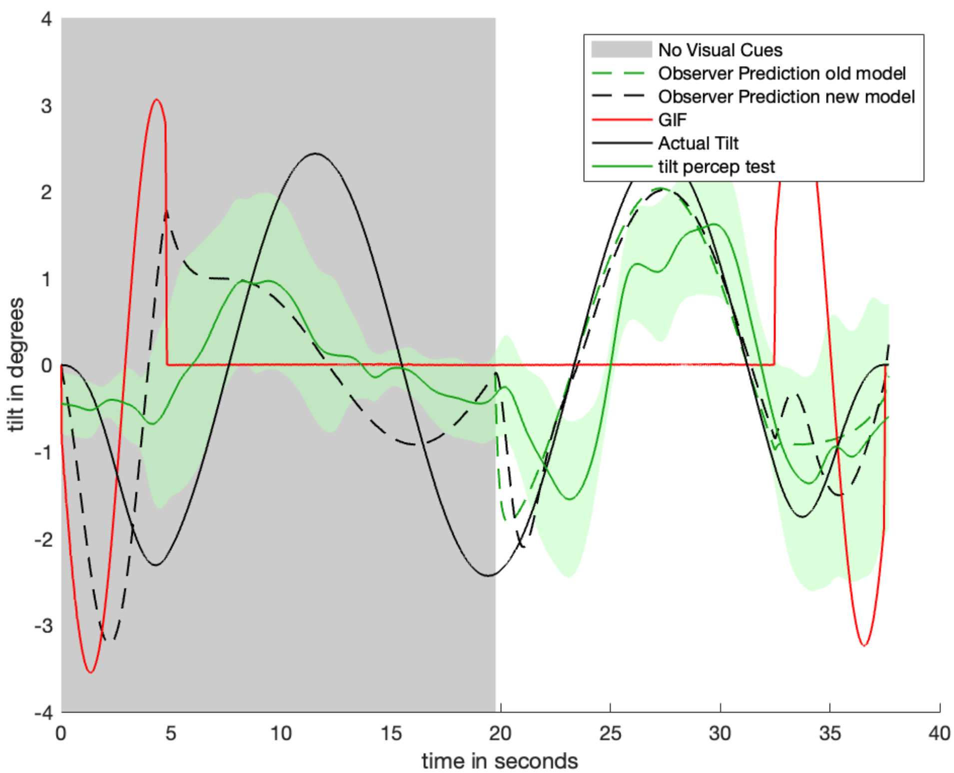
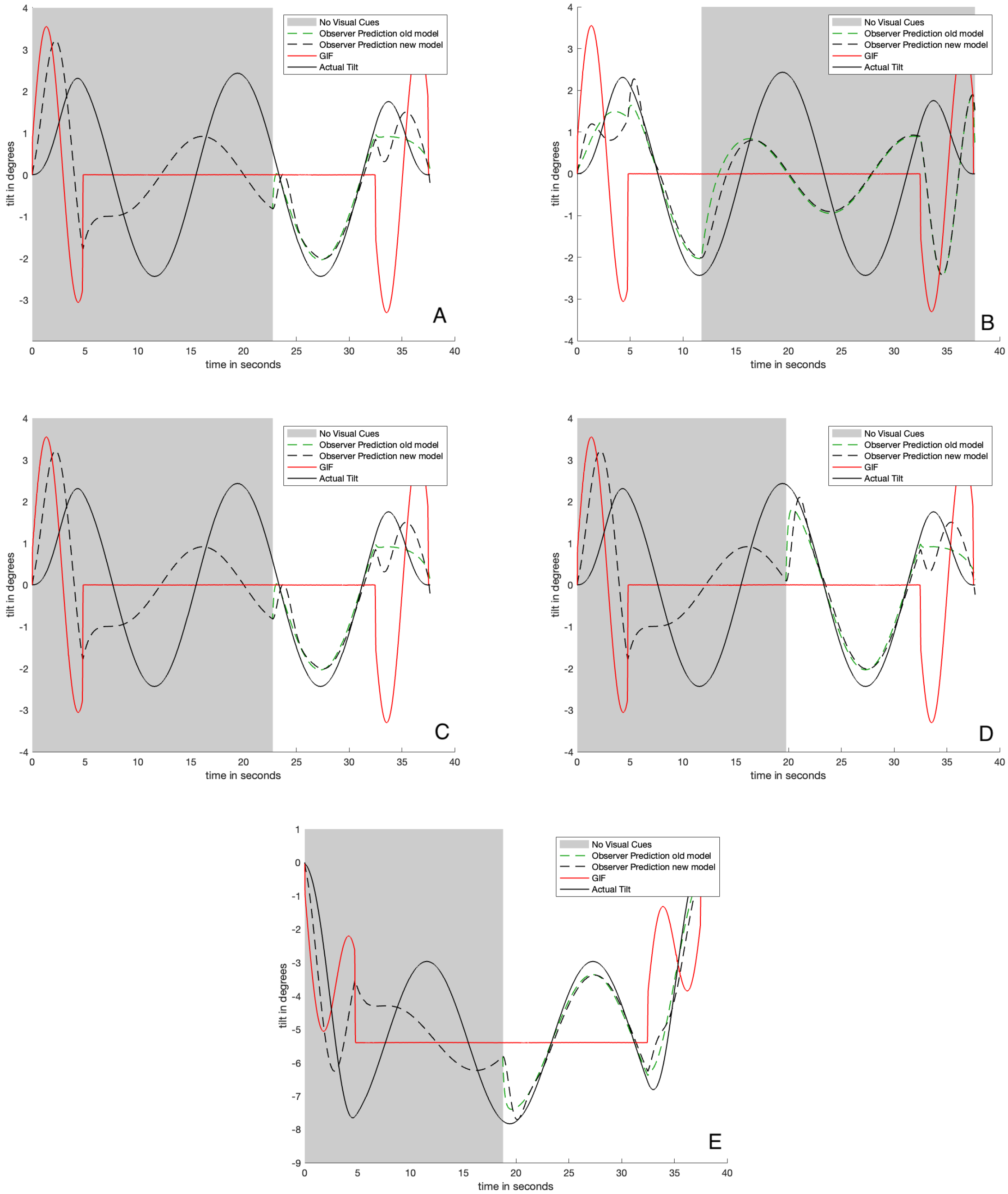


Figure 7.13: Plot matrix to show difference between original and updated model predictions.



verify that the updated model did not differ substantially from the original model when visual cues were always available. Figure 7.14 shows model predicted perceptions (where visual cues were always available) for the original and updated models. The updated model does change slightly for motions where visual cues were present the entire time. However, the differences between the two predictions were relatively small (less than 1 degree).

7.5 Discussion and Conclusions

As noted in Specific Aim One, the use of virtual reality is a limitation. Previous studies have found inconclusive results as to whether visual motion cues as delivered via virtual reality result in the same perception as when cues are delivered naturally [Ivanenko et al., 1998] [Kimura et al., 2017] [Pretto et al., 2009]. In contrast to findings in Specific Aim One, subject responses via the haptic bar task were less variable than expected. The task itself (as compared to the button press task described in Specific Aim One) provides far less blunt data. In Specific Aim One, subjects were only able to give an input each time they had rotated 90 degrees, sometimes this meant several seconds between button presses. The haptic bar task used in Specific Aim Two, however, resulted in near constant subject input.

A major limitation of Specific Aim Two, however, is that the original observer model is not quantitatively or qualitatively similar to subject responses in the absence of visual cues. The data presented in Specific Aim Two would imply during a shear cancelling motion at low frequency and small tilt angles, subjects perceive almost no sensation of tilt. The model (parameterized as presented by Newman, 2009), however, predicts an out of phase perception of tilt, shown in Figure 7.15. It may be possible to change nuisance parameters (such as gains within the vestibular portion of the model) in order to have the model better match the experimental data. However, given that the data presented in Specific Aim Two came from just three motion profiles, the model would certainly become overfit had I used the "no visual cues provided" control conditions to tweak nuisance parameters in the existing model before making updates. Further, the goal of Specific Aim Two was to measure and model tilt perception across a transition in visual cue availability

Figure 7.14: Plot to compare original (yellow dashed) and updated model (black dashed) predictions of tilt perception with visual cues available the entire time.

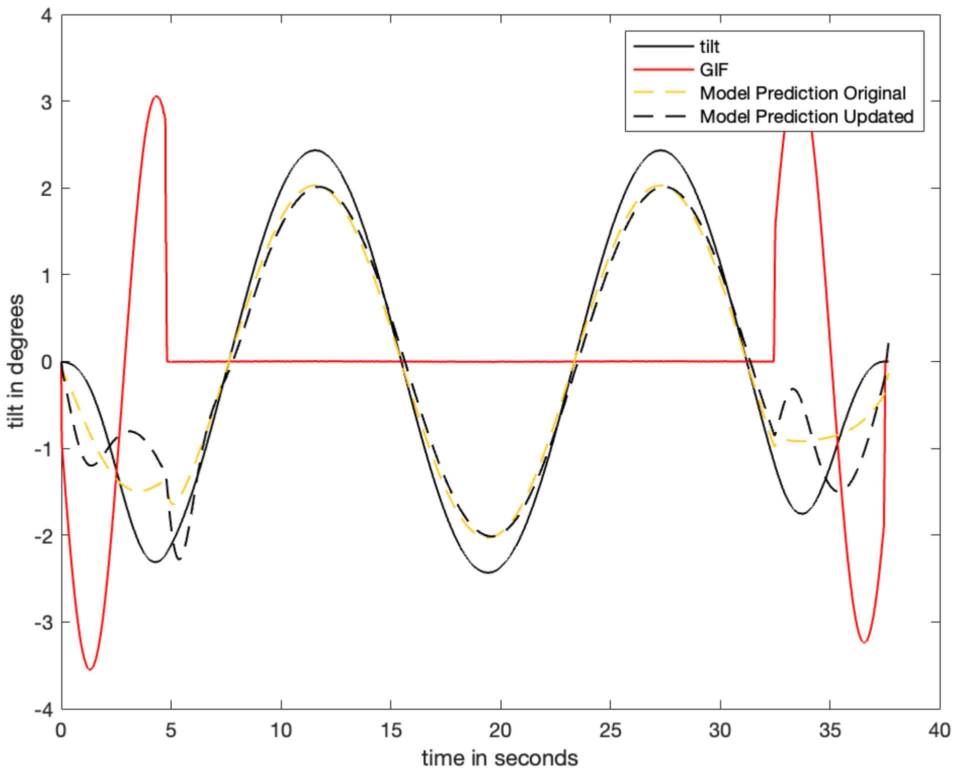
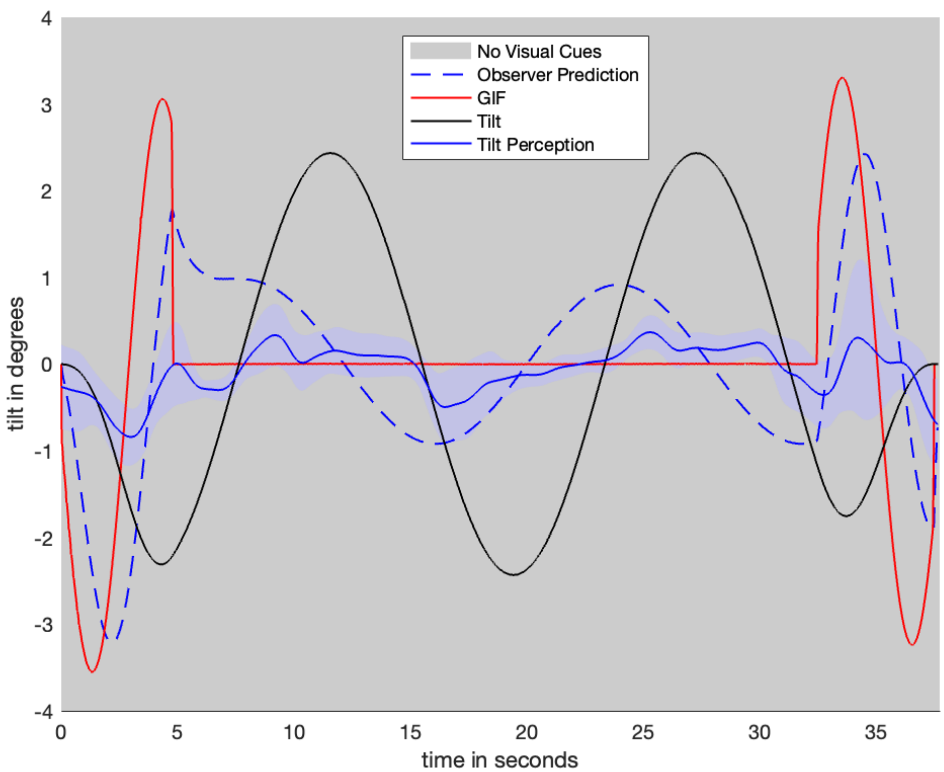


Figure 7.15: Observer prediction without visual cues is not consistent with subject data.



and not to verify or adjust existing model parameters. Therefore, I chose to ignore the discrepancy between the data and existing model prediction in the "no visual cues provided" control condition.

7.6 Summary

In Specific Aim Two, I have quantified tilt perception during sudden transitions in the availability of visual cues in roll tilt. I have made further changes to the Newman, 2009 observer model of orientation perception such that it is consistent with experimental data presented in this aim. The changes made to the model do not substantially change its predictions for previously verified scenarios (such as the one shown in Figure 7.14). The changes made to the model have no impact on any conclusions made in Specific Aim One because the changes in Aim Two were made only in a model pathway that is not stimulated by the types of motions used in Specific Aim Two.

Chapter 8

Specific Aim Three

8.1 Introduction

In Specific Aim Three, I quantified orientation perception and orientation awareness under the influence of sudden transitions in the availability of an attitude indicator. For example, an attitude indicator has a small field of view that does not naturalistically induce a sensation of self-tilt but does give the pilot awareness of their tilt angle. In Specific Aim Three, both orientation perception and orientation awareness where quantified via two separate experimental tasks. Overall, Specific Aim Three sought to quantify orientation perception and orientation awareness immediately following a sudden transition in the availability of an attitude indicator.

8.2 Experimental Methods

Specific Aim Three used the same three underlying motion profiles that were used in Specific Aim Two, combining roll tilt and lateral translation. The motion profiles were specifically designed to elicit misperceptions of tilt because of lateral translation to induce a change in net gravitational internal force. I used the same motion device used in Specific Aim Two (the TTS). Instead of presenting visual perception cues, here in Specific Aim Three, I presented subjects with an attitude indicator that is shown in Figure 8.1. The attitude indicator always provided accurate information and was designed to give subjects roll tilt awareness without stimulating naturalistic visual perceptual pathways, much like the attitude indicator found in typical aircraft pilot instrumentation. The attitude indicator had tick marks every 10 degrees and at 5 degrees. The 10- and 5-degree tick marks were specifically labelled, other tick marks were not labelled because the highest tilt angle experience across all motion profiles was 8 degrees.

In Specific Aim Three, I measured both tilt perception and orientation awareness with and without the presence of an attitude indicator. In order to quantify both orientation awareness and perception, I employed two experimental tasks, performed on separate trials: one psychophysical perceptual task and one awareness task to capture the nuanced differences between perception and awareness of orientation.

Similar to Specific Aims One and Two, four different visual cue availability conditions were used in both tasks for Specific Aim Three:

- Attitude indicator available entire trial
- Attitude indicator suddenly becomes available part way through trial
- Attitude indicator suddenly disappears part way through trial
- No visual or instrument information available entire trial (i.e., in the dark)

The TTS is a darkroom. Therefore, during periods of "no instrument or visual information available," prior to the attitude indicator appearing and following its disappearance, subjects had no visual information because they were in darkness.

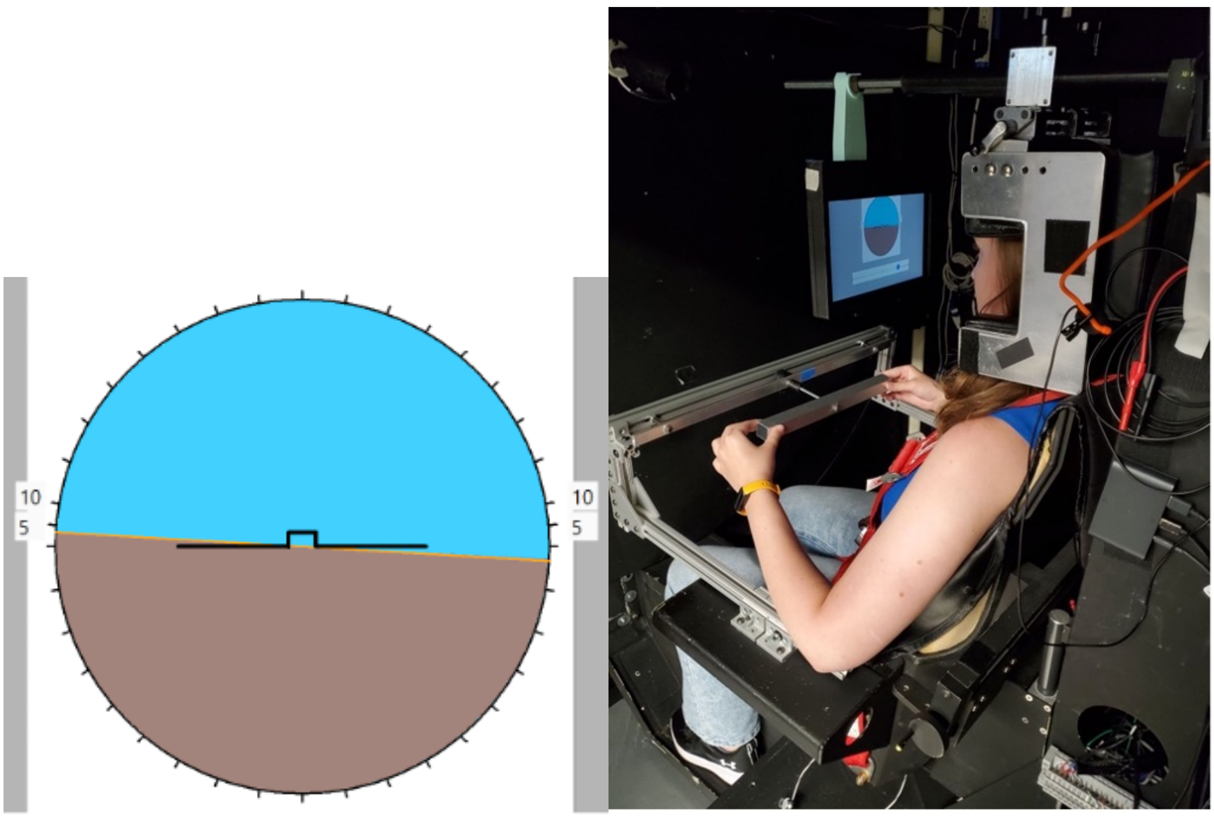
8.2.1 Task 1: Perception

The same haptic bar task used in Specific Aim Two (Experimental Methods) was used to measure perception of orientation in Specific Aim Three: Subjects were tasked with holding a haptic bar horizontal relative to Earth (see Figure 7.2) for the duration of each trial.

8.2.2 Task 2: Awareness

To measure awareness of roll tilt, I used verbal callouts. At pre-determined timepoints during each motion, subjects heard an auditory beep. Upon hearing the beep, subjects were instructed

Figure 8.1: Screenshot to show attitude indicator (left). Subject in apparatus (right).



to verbally call out the direction and number of degrees to which they thought they were tilted (or to call out zero if they felt they were upright). They were instructed to use the alignment of left ear down is left; right ear down is right. For example, if they felt they were tilted 2 degrees to the right at the time the beep happened, they called out "right 2". If a subject did not report their perceived tilt angle within 2 seconds (or did not report at all), they "missed" that callout and their response was not recorded. Subjects were not explicitly told about the two second reporting period so as to reduce pressure on the subject. Since the verbal callout methodology only yielded reports at discrete time points, and it was infeasible to have beeps requesting callouts spaced in intervals of less than 5 seconds, subjects completed each motion profile and attitude availability condition twice but with the verbal callouts at different (interleaved) time points. For example, run 1 of a condition contained a verbal callout at 20 seconds and run 2 contained a verbal callout at 22 seconds. Multiple runs of the same condition were required to obtain verbal callouts 2 seconds apart because they could not both be completed within the same trial. The verbal callouts were timed such that there was one callout 2 seconds prior to a transition (the maximum allowed time for a subject's response to be recorded) and one second after a transition.

8.2.3 Test Procedure

Subjects completed either Task 1 or Task 2 in a single testing session that lasted approximately one hour. Testing sessions for Task 1 and Task 2 were not combined due to the difficulty associated with switching between tasks and length of testing session. This difficulty was identified during pilot testing.

Subjects for both tasks were screened for self-reported 20-20 vision (use of corrective lenses, including glasses, accepted), no known history of vestibular dysfunction, and were between the ages of 18 and 40 at time of testing.

8.2.3.1 Task 1: Perception

Subjects completed two practice trials (one with the attitude indicator and one without) in order to gain familiarity with the haptic bar task. The practice trials were roll tilt only motions because these types of motions are easy to accurately perceive. Subjects were able to complete additional practice trials, but none wished to do so. Subjects then completed 18 test trials. Subjects only completed 9 test trails (3 motion profiles across 3 visual cue availability conditions) because the perceptual task and motion profiles were the same ones used in Specific Aim Two. In Specific Aim Two I already collected a full suite of test trial data during the "no visual cue provided" condition which is identical to the "no indicator provided" condition in Specific Aim Three (i.e., in the dark with no additional information/cues provided). Therefore, I did not recollect data for the "no indicator provided" condition and have re-used data from Specific Aim Two in analysis for Specific Aim Three.

8.2.3.2 Task 2: Awareness

Subjects completed at least four practice trials in order to gain familiarity with the verbal callout task. Subjects received the specific instructions: "You will be asked to verbally report the angle (in degrees) to which you cognitively believe you are tilted and the direction to one degree. E.g. "2 left"". Two practice trials occurred with the attitude indicator and two without. All practice trials occurred in roll tilt only (i.e., no translation motion). During practice, subjects were given feedback in real time. Immediately after a subject made a verbal callout, the experiment operator would (verbally) provide feedback on whether the direction of that callout was correct. Subjects had to accurately verbally call out the direction of their tilt for two practice trials in a row before they were offered to start test trials. I was less concerned with the magnitude of tilt called out during practice than I was about ensuring subjects accurately called out their perceived direction of tilt. About half of the subjects completed one or two extra practice trials in addition to the four required practice trials. Some subjects struggled with which direction was left vs right.

Subjects then completed 24 test trials (2 trial replicates per visual cue availability condition, 4 visual cue availability conditions, across 3 different motion profiles).

8.2.4 Data Processing

In Task 1 (the haptic bar task), I used the same data processing method described in Specific Aim Two. Briefly, subject responses were adjusted based on the average tilt of the true motion. For example, during the shear cancelling motion, the average tilt is 0 degrees. Therefore, if a subject's average perception during a shear cancelling motion was 1 degree, I subtracted 1 degree from the subject's haptic bar response at each discretized timestep during that trial.

In Task 2, no data adjustment was applied. All awareness data is presented as is.

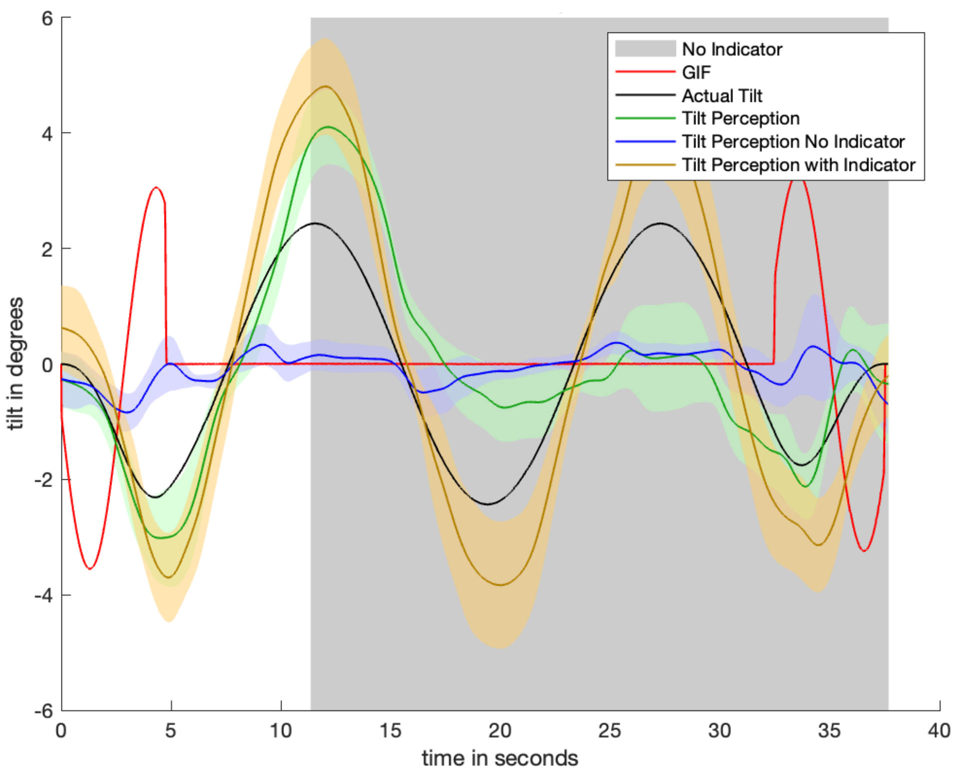
8.3 Experimental Results

8.3.1 Task 1: Perception

6 subjects (2 female; mean age 26 $\pm$ 3 years; 6 white) completed the full course of testing. Shown in Figure 8.2 is a full plot including perception during the sudden loss of the attitude indicator as well as perception during the two control conditions (where the attitude indicator was always available or never available). Notably, there is a marked difference in perception between the two control conditions (shown in orange and navy).

Figure 8.3 shows all remaining data collected in Task 1 of Specific Aim Three. In contrast to findings in Specific Aim Two, the "indicator suddenly appearing" conditions indicate that there is a substantially longer time associated with integrating sudden visual information. Shown in Figure 8.3 (panels B, D, and E), it appears to take 5+ seconds for the test condition (shown in green) to converge towards the "with indicator" (orange) control condition. During transitions in the other direction (indicator suddenly disappearing), however, the dynamic transition duration in perception appears similar to that found in Specific Aim Two. In Figure 8.3 (panels A and C) and in Figure 8.2, it takes around ten seconds for the control condition (green) to go from looking

Figure 8.2: Two control conditions (navy and orange) with test condition (green) showing perception of tilt.



similar to the orange line to looking similar to the navy line.

Additionally, during the shear doubling profile (Figure 8.3, panels A and B) there is some phase shift between the two control conditions. Surprisingly, tilt is overestimated when the attitude indicator is available vs relatively accurately perceived during its absence. Overestimation of tilt when the attitude indicator is present, however, is seen across all test conditions where the attitude indicator was available.

8.3.2 Task2: Awareness

9 subjects (3 female; mean age 24 SD $\pm$ 4 years; 7 white and 2 more than one race) participated in the experiment. 3 of the 9 subjects did not complete the full course of testing due to device malfunction during their testing session. If a subject missed a callout, their response was not included in that aggregate callout. Therefore, while 9 subjects participated in testing, not every single aggregate verbal callout has 9 data points. Each aggregate verbal callout presented has at least 6 data points. The full course of testing involved 96 verbal callouts (4 callouts across 24 trials), and, on average, each subject missed 4.5% of their verbal callouts (either due to late report or no report). The "stars" (Figure 8.4) are mean reported tilt, and the bars are the standard error.

Across all motion profiles there was a marked difference between the two control conditions (attitude indicator always available vs nothing presented visually). Figure 8.4 shows aggregate callout data for one motion profile, one test condition (green) and the two control conditions (navy and orange). Callouts during the control condition in which nothing was displayed (navy) are correct in direction (i.e., negative, or left ear down) but quite variable and appear to drift whereas callouts during the control condition in which the attitude indicator was always available (orange) are accurate to the true tilt angle and direction. As expected, the test condition (green) is initially consistent with the control condition in which nothing was displayed. After the transition of the attitude indicator becoming available, however, the test condition (green) is consistent with the control condition in which the attitude indicator was displayed the entire time (orange) immediately. Aggregate data for the first callout after the attitude indicator suddenly becomes available is

Figure 8.3: Plot matrix to show experimental data collected in Aim Three, Task 1: Perception.

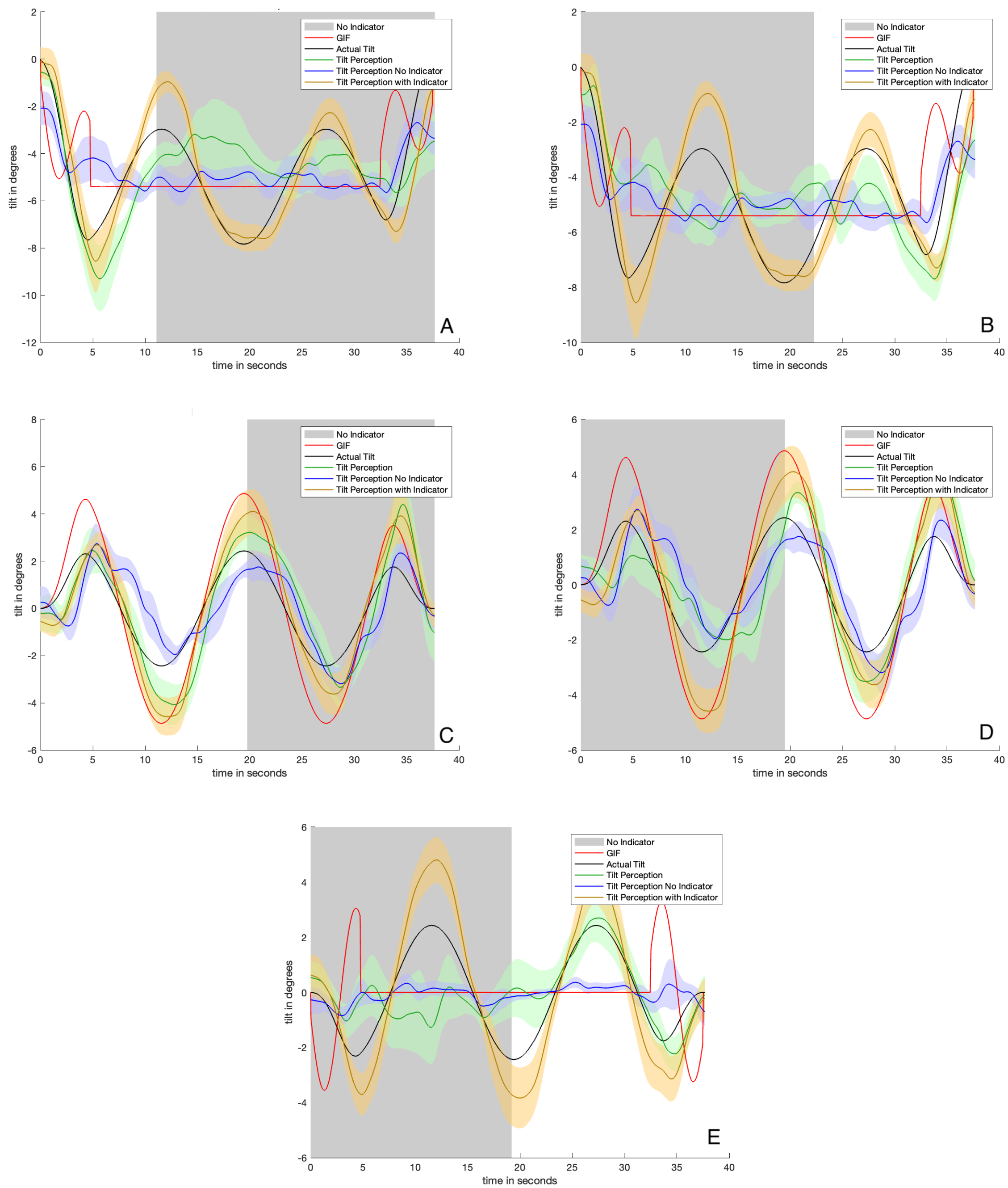
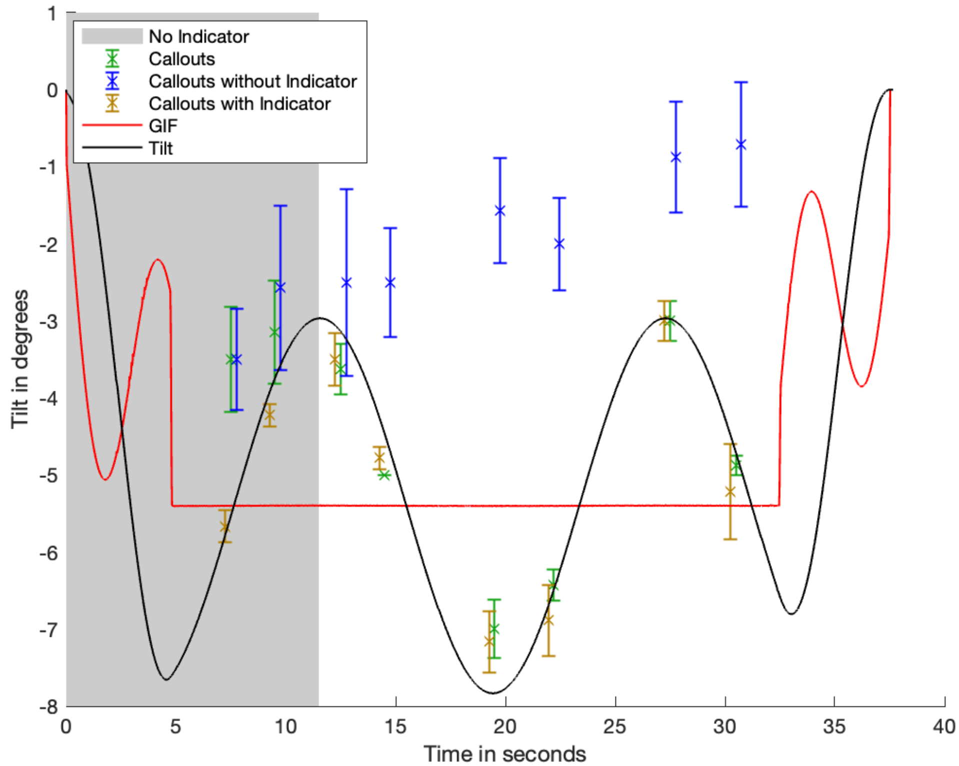


Figure 8.4: Callouts are shown as an average (star) and standard error (bars). The two control conditions are shown in navy and orange.



already fully consistent with the corresponding control condition. The pattern of accurate awareness immediately following the sudden appearance of the attitude indicator was observed across all motion profiles.

Conversely, when the attitude indicator suddenly disappears (Figure 8.5, panels A, C, and E) aggregate awareness data does not immediately drift and become more variable (as is seen in the corresponding, navy, test condition). Across the three motion profiles, there is evidence of gradual temporal dynamics before the test condition (green) is fully consistent with the control condition (navy). Additionally, it appears that precisely how long it takes for the test condition (green) to become consistent with the control condition in which nothing was displayed visually (navy) varies between motion profiles.

Figure 8.6 characterizes awareness of tilt following a transition in the availability of an attitude indicator. Figure 8.6 is a visualization of how long it takes for each test condition examined in the callout task of Specific Aim 3. The navy portions of Figure 8.6 indicate times at which the callouts for that test condition were consistent with callouts of the control condition in which nothing was displayed visually. The orange portions indicate times at which the callouts of the test condition were consistent with callouts in the control condition where the attitude indicator was always displayed.

Notably, in the test conditions where the attitude indicator suddenly became available, the callouts went from being consistent with the navy control condition to the orange control condition by the first callout after the attitude indicator appeared. This implies that it took less than 1 second for subjects to integrate the sudden information into their orientation awareness. There was more variability in transitionary behaviour in the case where the attitude indicator suddenly disappeared. I computed an average time taken for awareness following a sudden disappearance of attitude indicator to match awareness while never having had an attitude indicator. I did this by computing the time between the transition and first verbal callout following the transition that was consistent with the control condition. I therefore ended up with 3 numerical values in seconds. The average of these three values was 7 seconds (7.3 to 1 decimal place) for orientation awareness

Figure 8.5: Plot matrix to show experimental data collected in Aim Three, Task 2: Awareness.

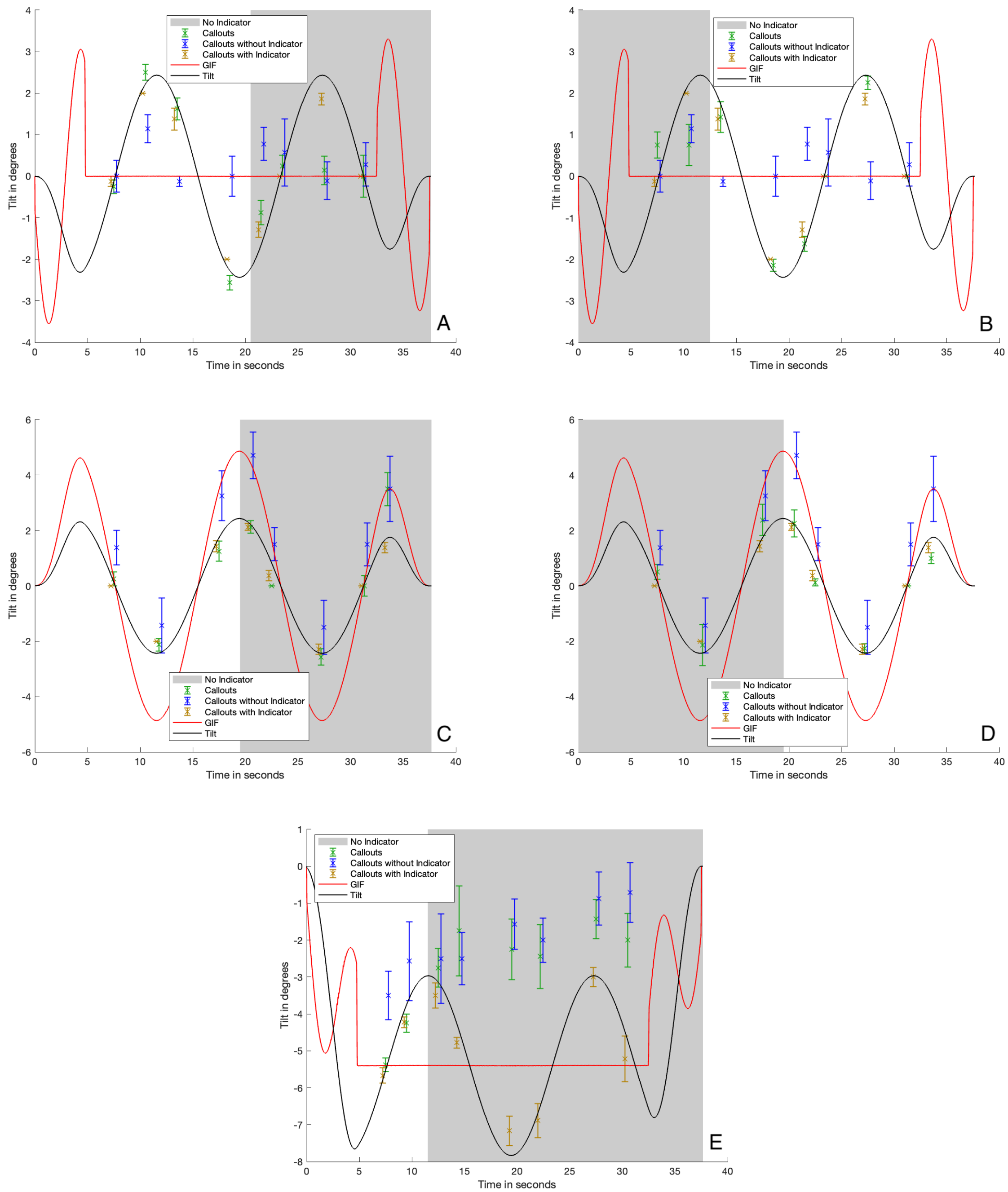
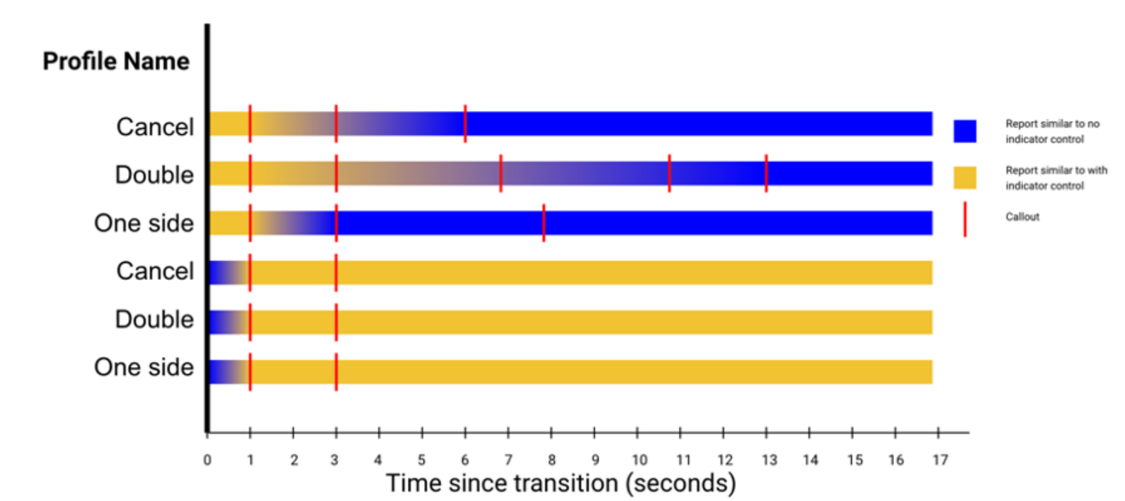


Figure 8.6: Graphic to visualize time taken for awareness to match respective control condition.



to transition between the two control conditions.

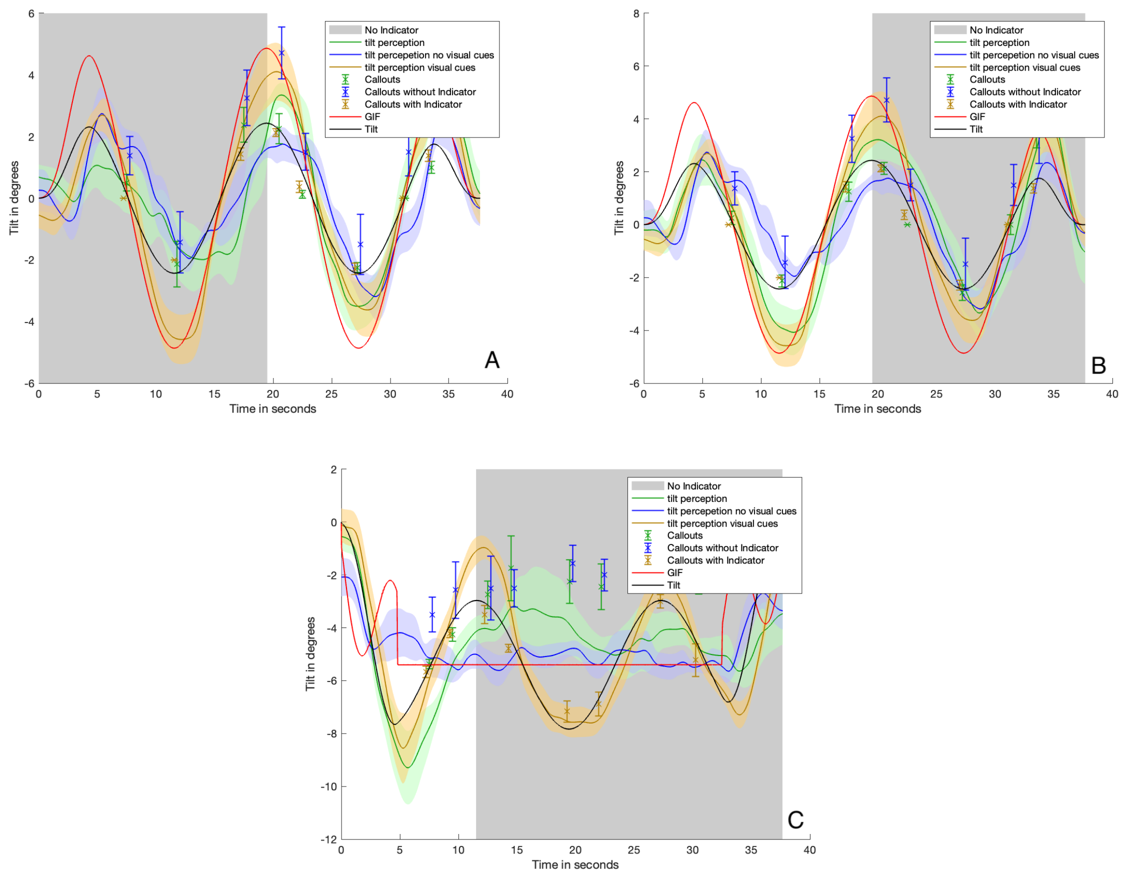
8.3.3 Comparison Between Task 1 and Task 2

While the same motion profiles were used between Task 1 and Task 2 of Specific Aim three, the transitions were not all at the same time. Data collection for Task 2 was done after data collection for Task 1. Based on analysis of Task 1, the time at which the transition occurred was changed in order to ensure the transition occurred at a time when there was likely a large difference between the two control conditions.

Figure 8.7 shows the three test conditions in which the motion profile and visual transition time were held constant. The aggregate awareness data (stars and bars) has been overlaid on top of the average perceptual data (lines).

In all cases, the aggregate awareness data was not fully consistent with the perceptual data. When the attitude indicator was never shown, perceptual data is more consistent with the net gravitational inertial direction than the awareness data which is generally in the correct direction but highly variable. Unsurprisingly, awareness data when the attitude indicator was displayed (with numeric tick marks) is more accurate to true tilt than the perceptual data. Based on the instructions given to subjects, I expected awareness and orientation to differ, even during the same motions. Subjects were instructed to report orientation (via the haptic bar) based on how they felt (the phrase "align the bar with what you feel is horizontal" was used in the instructions). For the awareness task, however, subjects were instructed to report based on information (as opposed to feeling). Additionally, there is a fundamental difference between reporting tilt and moving a haptic bar. Verbally reporting tilt requires the subject to consider their orientation and then consciously verbalize what they believe their current tilt angle to be. Holding a bar horizontal is a more intuitive task that does not require an additional layer of cognition.

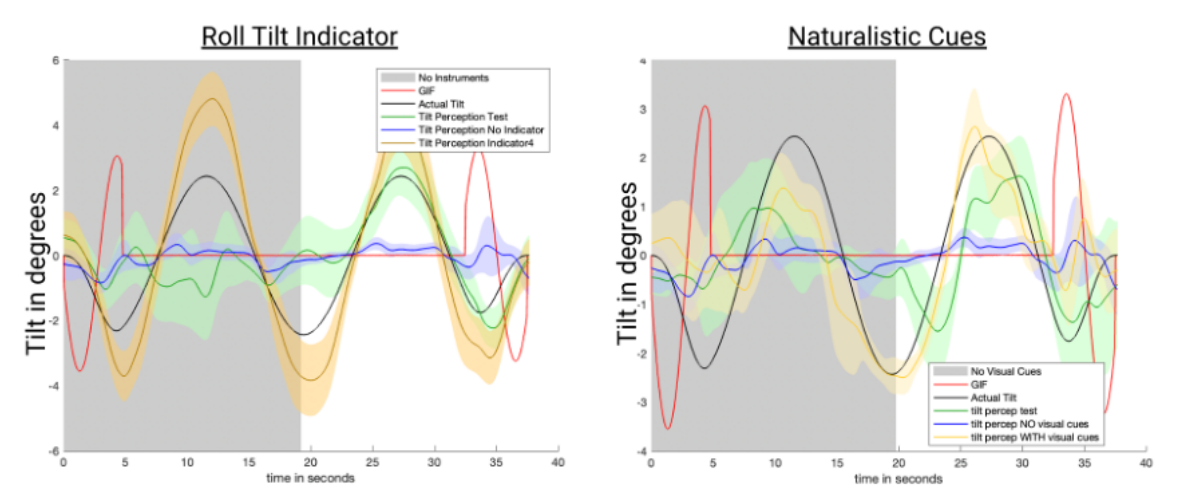
Figure 8.7: Full suite of data from both the perceptual and callout task.



8.4 Discussion and Conclusion

Data from Task 1 of Specific Aim Three indicates a delayed and gradual integration of new attitude indicator information into perception of tilt. However, data from Task 2 indicates almost immediate integration of new attitude indicator information into awareness of tilt. Data from both Task 1 and Task 2 indicates that past visual information from an attitude indicator impacts both perception and orientation awareness for approximately 8 seconds after the indicator disappears from field of view. Perceptually, the data from Specific Aim Three shows that cues from an attitude indicator are not as quickly integrated into tilt perception as naturalistic visual cues (Specific Aim Two). Figure 8.8 (left) shows perception with an attitude indicator and Figure 8.8 (right) shows perception with naturalistic visual cues.

Figure 8.8: Comparison between perceptual responses with the attitude indicator (left) and naturalistic visual cues (right).



The underlying motion profile is the same (the control condition data where nothing was displayed is also the same). They key difference is how quickly the new visual information is integrated following the visual transition occurring around 19 seconds into the trial. The visual transitions did not happen at quite the same time. However, the 5-second-long delay seen following the transition in Figure 8.8 (left) is much longer than the 1-second-long delay seen in Figure 8.8

(right). A key difference found in Specific Aim Three is the slower integration of new attitude indicator into perception when it suddenly becomes available.

Noted earlier, subject callouts were quite variable in the "no visual information displayed" control condition of Task 2. The high variability may be indicative of subjects not knowing (i.e., lacking awareness of) their current tilt. This contrasts with perceptual data in the same visual information availability condition: In the perceptual task, there is no immediately visible difference in the standard error surrounding the "with attitude indicator" (orange) condition vs the "no visual information" (navy) condition. It appears that during the perceptual task, subjects consistently misperceived their roll tilt whereas in the callout task, subjects may have been unaware and simply guessing their roll tilt state. Future work could involve adding a confidence report to the verbal callout task of orientation awareness to determine if there is a difference in confidence of report with vs without the attitude indicator. Data from Specific Aim Three implies that orientation awareness and orientation perception may not be entirely independent processes. Loss of awareness might imply that orientation is simply unknown whereas misperception implies feeling oriented in a way that is different from true orientation. The term "awareness" in this context is consistent with the use of "awareness" in skydiving and flight. When a skydiver loses altitude awareness, it is generally assumed that they do not know their altitude and not that they believe they are at a different altitude from their true altitude.

The use of low pass filtering to reconcile model predictions with perceptual dynamics following a sudden visual transition was successful in both Specific Aim One and Specific Aim Two. The brain does not assume that new information which disagrees with expected sensory measurements should immediately be integrated into perception. Notably, in all Specific Aims, subjects were explicitly informed that any visual cues were reliable and accurate. Despite having been informed of the accuracy of any visual information, only in the orientation awareness task do we see almost immediate integration of visual information. It appears that although subjects understood that the visual information was correct (as per results in the orientation awareness task), some level of subconscious perceiving resulted in a gradual integration of the sudden visual cues. It is possible that, although subjects are aware of the accurate visual information, the brain takes time to disambiguate the possibility of visual information due to surround motion vs self motion.

8.5 Summary

In Specific Aim Three I have quantified tilt perception and tilt awareness across sudden transitions in the availability of instrumentation. Notably, via effective experimental design, I have captured the characteristic differences in the way human subjects integrate the same information into their perception vs awareness of tilt. I have shown that human subjects gradually integrate sudden instrumentation information into their perception of tilt but appear to essentially immediately integrate such information into their awareness of tilt. Additionally, I have shown that the gradual integration of instrumentation information appears to take longer than the integration of sudden visual cues (comparison shown in Figure 8.8).

Chapter 9

Thesis Conclusions

9.1 Scientific Implications

9.1.1 Gradual Integration of Sudden Naturalistic Visual Cues

In both Specific Aims One and Two, the sudden appearance of naturalistic visual cues resulted in a gradual (and not discontinuous) change in orientation perception. This thesis is the first quantification of tilt or angular velocity perception following sudden appearance of naturalistic visual cues. The scientific implication is that sudden orientation cues that disagree with existing orientation may not be immediately integrated into the brain's estimate of spatial orientation.

9.1.2 Prolonged Perceptual Decay Following Sudden Loss of Naturalistic Visual Cues or Instrumentation Cues

In all of Specific Aims One, Two, and Three, the sudden loss of visual cues did not result in immediate change in tilt or angular velocity perception. In all Specific Aims, there was a prolonged period in which orientation perception transitioned from a "perception with visual cues" to a "perception without visual cues" pattern of orientation perception. The scientific implication is that past visual cues continue to impact orientation perception for many seconds even after they have disappeared.

9.1.3 Low Pass Filtering in CNS Processing of Orientation Perception

The addition of low pass filtering for the visual sensory conflict pathways allowed for a model of orientation perception that was robust to sudden changes in visual cue availability. The scientific implication is that low pass filtering may be the mechanism occurring in CNS processing of sudden visual orientation information. Notably, while the newly presented model captures perceptual dynamics measured across a range of motion types, it is only one plausible modelling approach. Being consistent with perceptual reports does not necessarily mean that low pass filtering is the mechanism the brain is employing.

9.1.4 Time Delayed Integration of Sudden Instrumentation Cues into Orientation Perception

It takes substantially longer to integrate sudden attitude indicator information into tilt perception than it does naturalistic visual cue information. The scientific implication is that naturalistic visual cues may not require additional cognitive processing in a way that may be required for information from an attitude indicator. This means that an additional cognitive layer of processing may be used during the integration of attitude indicator information into orientation perception.

9.1.5 Rapid Integration of Sudden Instrumentation Cues into Orientation Awareness

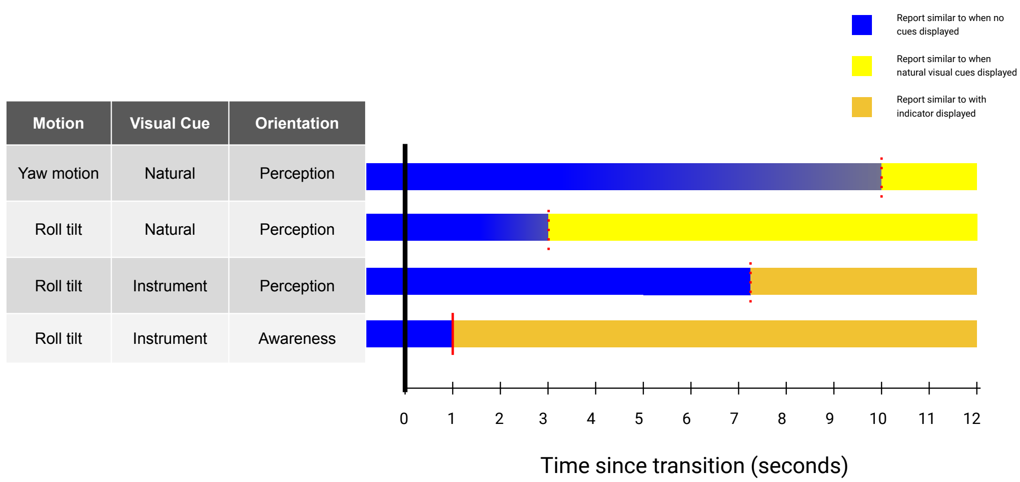
Conversely, attitude indicator information is almost immediately integrated into awareness of tilt. Immediately following the sudden appearance of an attitude indicator, subjects are able to accurately report their awareness of tilt as though they had an attitude indicator present the entire time.

9.2 Summary of Scientific Implications

This thesis has quantified the dynamics of perception and awareness of orientation following sudden transitions in the availability of naturalistic visual cues or an attitude indicator. Figure

9.1 summarizes the different integration timeframes following a sudden gain of visual information. Figure 9.2 summarizes (visually) perceptual and awareness dynamics following a sudden loss of visual information.

Figure 9.1: Visualization of time take to integrate sudden gain of visual information.



It is important to note the different time scales between the visualizations shown in Figure 9.1 and Figure 9.2. The timeframe for integration of sudden visual information is much shorter than for the sudden disappearance of visual information. Additionally, the main difference comes from how long it takes naturalistic visual angular velocity cues to stop impacting perception of orientation.

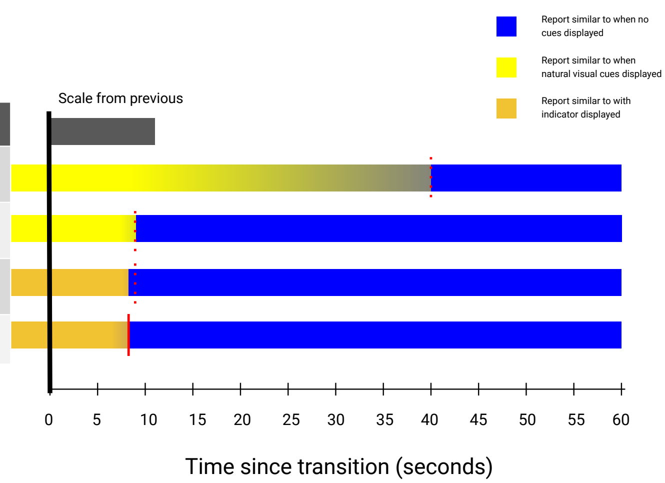
9.3 Contributions

9.3.1 Quantification of Angular Velocity and Tilt Perception Following Sudden Transitions in Visual Cue Availability

This thesis is the first characterization of orientation perception following a sudden transition in the availability of naturalistic visual cues. It is the first quantification of both angular velocity and tilt perception.

Figure 9.2: Visualization of time take to integrate sudden loss of visual information.

Motion	Visual Cue	Orientation
Yaw motion	Natural	Perception
Roll tilt	Natural	Perception
Roll tilt	Instrument	Perception
Roll tilt	Instrument	Awareness



9.3.2 Novel Model of Orientation Perception that is Robust to Sudden Visual Transitions

Presented in this thesis is a novel model of orientation perception that is robust to sudden changes in visual cue availability. The novel model accurately predicts angular velocity and tilt perception following sudden loss or gain of visual angular velocity or visual verticality cues, respectively. While it is impossible to be certain that the brain is employing low pass filtering, the enhanced model is functionally capable of predicting orientation perception across several motion profiles and paradigms following sudden transitions in visual cue availability.

9.3.3 First Implementation of Quantitative Parameter Fitting for an Observer Model

Prior to this thesis, neither nuisance parameters nor added free parameters (e.g., time constants) were quantitatively fit in an observer model of orientation perception. Additionally, the process of tuning an observer model on training data and later comparing it to test data which was not used to tune the model does not appear in existing literature. Given that the model is successful in predicting orientation perception during motions that were not used to train the model, the model is, therefore, more likely accurately predict orientation during any arbitrary motion profile.

9.3.4 Quantification of Tilt Perception and Awareness Following Sudden Transitions in Instrumentation Availability

This thesis is the first presentation of the quantification of both perception and awareness following the sudden appearance and disappearance of an attitude indicator. The measurement or orientation and awareness on the same motion device with the same motion profiles additionally allows for direct comparison between the two.

9.4 Summary of Contributions

Over the course of this PhD, I have quantified motion perception and orientation awareness perception following sudden transitions in the availability of naturalistic visual cues or an attitude indicator. I present a novel model of orientation perception that accurately predicts tilt and angular velocity orientation perception following sudden transitions in naturalistic visual cue availability. Additionally, I present a quantitative method for setting model parameters based on experimental data.

9.5 Limitations

9.5.1 Study Size and Representation

Each experiment within this thesis has between 6 and 17 participants. Although it was possible to collect sufficient data to reasonably quantify perception and awareness of orientation, the sample size is still quite small. Additionally, the majority of subjects were male and white in each experiment. Although, the subject pool is generally representative of (and perhaps more diverse than) the population of pilots at large, these results would be more applicable to pilots in the future had the subject pool been more representative of the general populace instead.

It can be beneficial to have study participants be demographically similar to current active-duty air force pilots (78% male, 70% white) [Military Report, 2023]. However, scientific studies designed around an unrepresentative population can result in hardware (such as the human machine interface of aircraft and spacecraft) which is not usable by the general population. Underrepresented persons may therefore experience an additional barrier to entry thus solidifying a self-perpetuating issue of lack of diversity in air force pilots.

9.5.2 Pilot Subjects vs Untrained Subjects

The overarching goal of this thesis was to make a meaningful contribution to scientific literature concerning the flight like scenarios of suddenly gaining or losing visual cues (e.g., flying into a cloud) or instrumentation cues (e.g., looking at or away from an instrument display). Therefore, with infinite resources, I would have had a pilot's license as part of the inclusion criteria. However, collecting data on subjects with pilot's licenses only was not possible due difficultly sourcing pilot subjects. Across all Specific Aims, a total of 3 subjects had a pilot's license. Having 3 subjects with pilot's licenses was insufficient to make comparisons between them and non-licensed subjects.

It is possible that subjects with extensive piloting experience may have performed better due to knowledge and personal experience with spatial disorientation illusions [Tribukait and Eiken, 2012]. Experience with continued yaw motion or motion combinations that result in interaural shear cancelling during flight may change how accurately someone could perceive angular velocity or tilt without visual information [Tribukait and Eiken, 2012]. Additionally, it is possible that during the perceptual task with (and without) the attitude indicator, an instrument rated pilot may have integrated information from the sudden appearance of the attitude indicator much faster than the subject pool used in this thesis. While future investigations should explore the effect of piloting experience, we note that in our study, the naturalistic visual cues and attitude indicator were simplistic, and subjects were provided training and familiarization.

9.5.3 Model Architecture does not Support Perceptual Variability

A limitation that came up later in the study was the difference in variability of subject responses across different visual information availability conditions. In Specific Aim One, subject responses in the "no visual cues provided" control condition qualitatively look like they are more variable than subject responses in other conditions (in which visual cues were available at least some of the time). More noticeably (and quantifiably), in Specific Aim Three, aggregate callout data is more variable in the "no visual information provided" condition than in the "attitude indicator provided" condition. As it stands, the current observer model architecture generates a single prediction perception of orientation for a given scenario and visual cue availability condition. The current model architecture's inability to also produce a confidence or variability rating for a given predicted perception is a major limitation: The higher variability in perception when visual information is not present is seen consistently throughout this thesis and is currently uncapturable in the model.

9.6 Future Work

The applicability of the results presented in this thesis is in the piloting of manually controlled aircraft and spacecraft. This thesis has aptly characterized and modelled both perception and awareness of orientation following sudden transitions in visual information availability including how quickly misperception or loss of awareness of orientation persists for. However, this thesis fails to quantify or describe how such misperceptions actually impact the control of an aerospace vehicle. To better design human machine interfaces or choreograph flight manoeuvres that reduce the change of aviation mishap, it will be necessary to understand how misperception and misunderstanding of orientation change pilot behaviour. Future work could, therefore, examine the underlying causal link between orientation awareness and perception with manual control.

The existing experimental hardware remains functional. Therefore, it is possible to achieve a larger dataset with a subject pool that is more representative of the population at large (rather than representative of military pilots). While unlikely that scientific conclusions will change with a larger dataset, with a larger subject pool, it will be possible to state that findings are applicable to a broader population. Future work could also center on measuring the impact (if any) of demographic information on perception of orientation. Such work, especially if no differences are found, could make the scientific findings of this thesis applicable to a far larger populace.

Additionally, the application of quantitative determination in changes of perceptual patterns could more concretely solidify results presented in this thesis. All perceptual data (Specific Aim One, Two, Three Task 1: Perception) was initially qualitatively analyzed to determine the time it took subjects to integrate new (or new loss of) information. It may be possible to apply statistical techniques in order to generate a rule based definition of when the test condition is consistent with one control condition or the other (or neither, thus indicating a transitional state).

Another avenue for future work is the use of different motion profiles, particularly in roll tilt.

The motion profiles used in this thesis were limited by the physical limitations of the motion device (TTS). As a result, all three motion profiles used in Specific Aim Two and Specific Aim Three had the same underlying tilt profile (but different translation profiles). With the use of a more capable machine (e.g., the Kraken located at NAMRU-D), more complicated motion profiles with larger tilts will be possible. I collected a large amount of additional data in Specific Aim Two which is not presented in the main body of this thesis because it was difficult to show substantial difference in perception between visual cue availability conditions. I believe that some of the difficultly I had in demonstrating different perception with and without visual cues was a result of tilts being limited to 3 degrees. When looking for perceptual differences on the order of 3 degrees, I needed subjects needed to perform the haptic bar task very precisely and consistently. With larger possible motion profiles (and therefore larger discrepancies in perception between visual cue availability conditions) I believe that it will be easier to discern differences in perception under different visual scenes. For example, a visual scene only containing visual angular velocities cues might impact perception of tilt in a measurable way. For the motion profiles used in Specific Aim Two, the tilt angles were too small to elicit different perceptions between no visual cues provided and only visual angular velocity cues provided.

Future work could study the differences in perception following sudden transitions in the availability of visual information in pilots vs non-pilots. Should there be differences between perception in pilots (which is very possible particularly where the visual information provided is in the form of an attitude indicator), further data could be collected on a flight trained subject pool.

Existing models of orientation perception do not include perception as influenced by non-naturalistic visual cues (such as the attitude indicator used in Specific Aim Three). New models of orientation could be adapted to include pathways for information as delivered by instrumentation. Additionally, existing models only predict perception of orientation. Pilots use a combination of perceived orientation and orientation awareness for the manual control of aircraft and spacecraft. To fully understand manual control dynamics, it will be necessary for models of perception to be extended to become models of perception and understanding of orientation. Future work should include extending observer models to also predict orientation awareness and not just perception.

Lastly, future modelling processes could change the underlying model framework in order to predict not just orientation perception but also the variability of that perception. The data presented in this thesis provides very compelling evidence that the variability of perception and awareness is impacted by the presence of visual information. The marked difference in variability of subject responses is seen both in perception and orientation awareness. Additional studies could also be performed to measure the variability of perception within a single subject. E.g., how consistent are humans when we perceive our orientation? A novel model may be able to capture both inter- and intra-subject perceptual variability.

Chapter 10

Final Words

In the absence of visual information, humans misperceive their orientation or misunderstand their knowledge of orientation even in relatively simply dynamic scenarios. The presence of visual information can reduce the magnitude of or entirely remove misperception or misunderstanding of orientation. Across angular velocity perception and roll tilt perception, humans do not immediately integrate visual information into their perception of orientation whether it appears as naturalistic cues or instrumentation. However, humans do rapidly integrate roll tilt information into their orientation awareness. In the inverse scenario, the sudden loss of visual information, preexisting naturalistic visual or instrument cues continue to impact perception and understanding of orientation after the cues have disappeared. This indicates that past information impacts current perception and awareness of orientation dynamics. The time taken for perception to change following a transition in visual information availability was generally much greater in the yaw motion experiment than the time taken in the tilt perception experiments.

Low pass filtering of visual horizontality and visual angular velocity resulted in reconciliation of the Newman (2009) observer model with the experimental data presented in this thesis. It is therefore possible that low pass filtering is occurring during central nervous system processing of sudden new or sudden loss of visual angular velocity or verticality cues.

Future work should focus on how these perceptual dynamics following a sudden visual cue availability transition impact the manual control of aircraft. Future work should also address applicability of the research presented in this thesis to underrepresented populations. Lastly, future modelling efforts should capture the vast differences in variability of perception and orientation awareness in the absence of visual information (naturalistic cues or instrumentation cues).

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Appendix A

Additional Data Within Specific Aim One

As noted earlier in this thesis, I collected more data than is presented in Specific Aim One. In this appendix is the full suite of data collected in Specific Aim One. The data presented below does not include pilot data. It includes data collected from subjects who met inclusion criteria, completed an informed consent, and performed some testing.

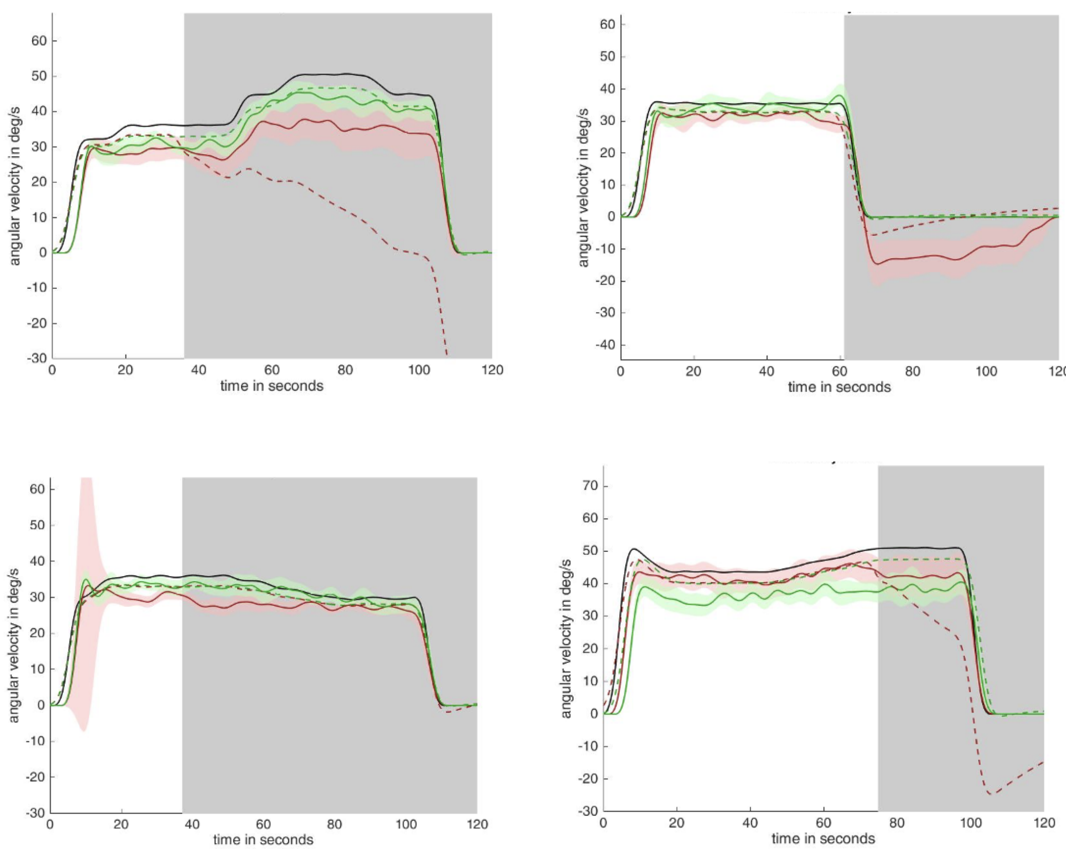
A.1 Unused Motion Profiles

Figure A.1 includes motion profiles that were ultimately not used in the final version of the experiment because there was no meaningful difference between the two control (red and green) conditions. Based on subjective reports from subjects during testing, I learned that highly consistent motion profiles (with limited change in angular velocity over time) were easy to predict. As a result, subjects could simply press the button in their left or right hand at a constant frequency in response. Therefore, subject perceptions during highly consistent motion profiles did not provide great data.

A.2 Additional Data

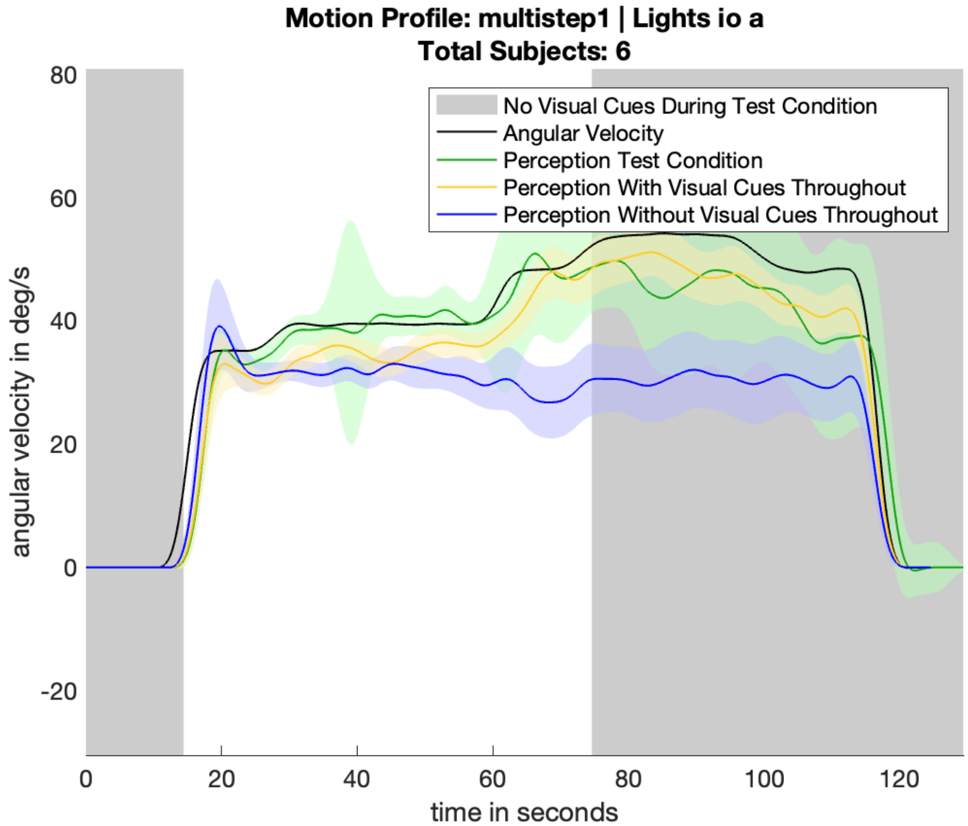
The following pages show all data collected in Specific Aim One. 6 of the 8 profiles presented were use in the analysis in the main thesis text. For the unused profiles and data, there is little to no difference between the two control conditions. Without a difference in perception between the two control conditions, there is little to be learnt from a test condition. If the presence of naturalistic

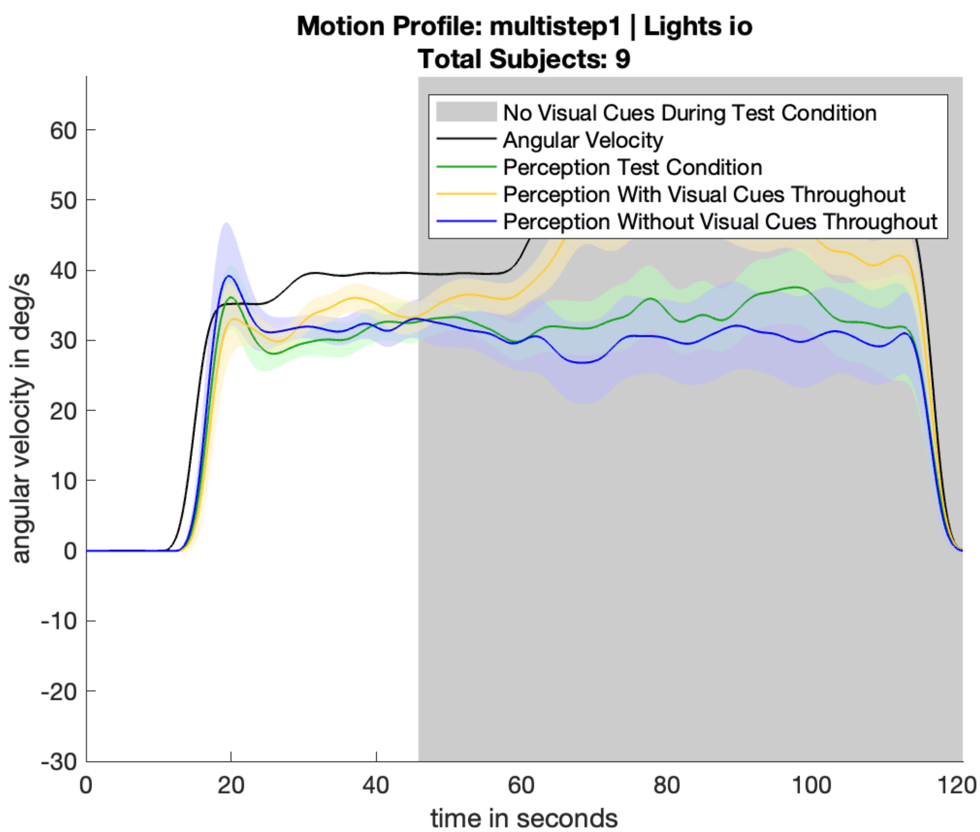
Figure A.1: Initial motion profiles not used in the final experiment.



angular velocity cues does not change perception substantially from perception without any visual cues, then having visuals cues suddenly appear or disappear should not change perception.

Figure A.2: The following pages (pp 103 - pp111) include a group of figures indicating additional data collected in Specific Aim One.


Motion Profile: multistep1 | Lights io a
Total Subjects: 6
No Visual Cues During Test Condition
Angular Velocity
Perception Test Condition
Perception With Visual Cues Throughout
Perception Without Visual Cues Throughout
angular velocity in deg/s
time in seconds
80
60
40
20
0
-20
0
20
40
60
80
100
120


Motion Profile: multistep1 | Lights io
Total Subjects: 9
No Visual Cues During Test Condition
Angular Velocity
Perception Test Condition
Perception With Visual Cues Throughout
Perception Without Visual Cues Throughout
angular velocity in deg/s
time in seconds
60
50
40
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60
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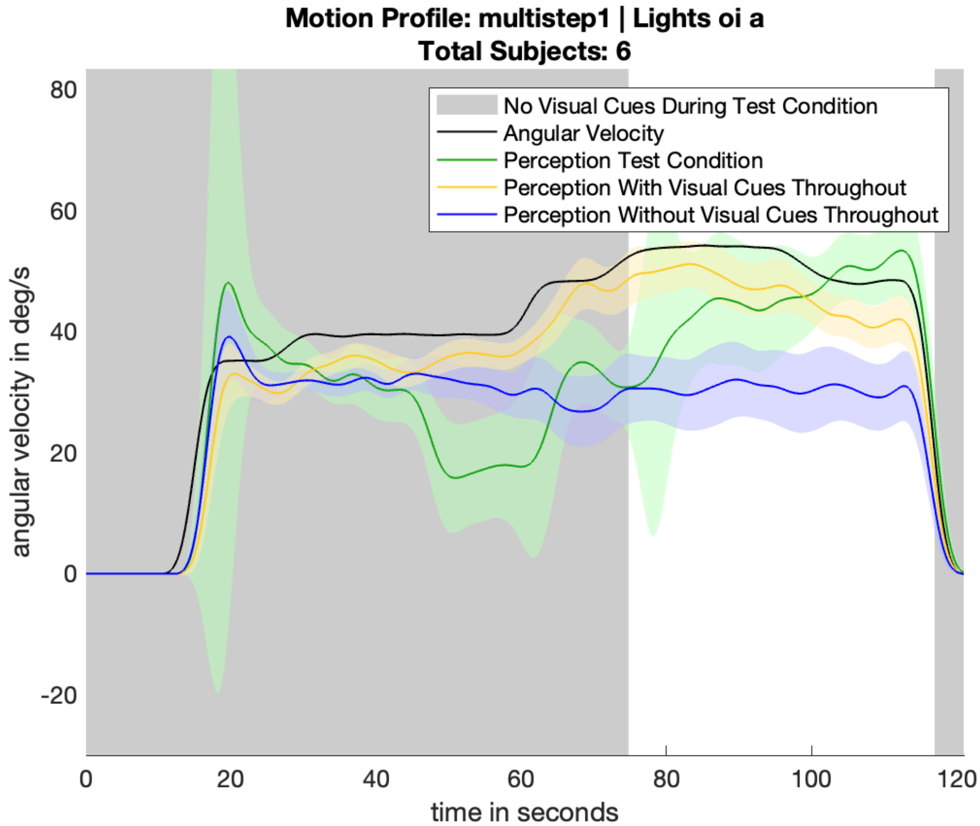
100
120


Motion Profile: multistep1 | Lights oi a
Total Subjects: 6
No Visual Cues During Test Condition
Angular Velocity
Perception Test Condition
Perception With Visual Cues Throughout
Perception Without Visual Cues Throughout
angular velocity in deg/s
time in seconds
80
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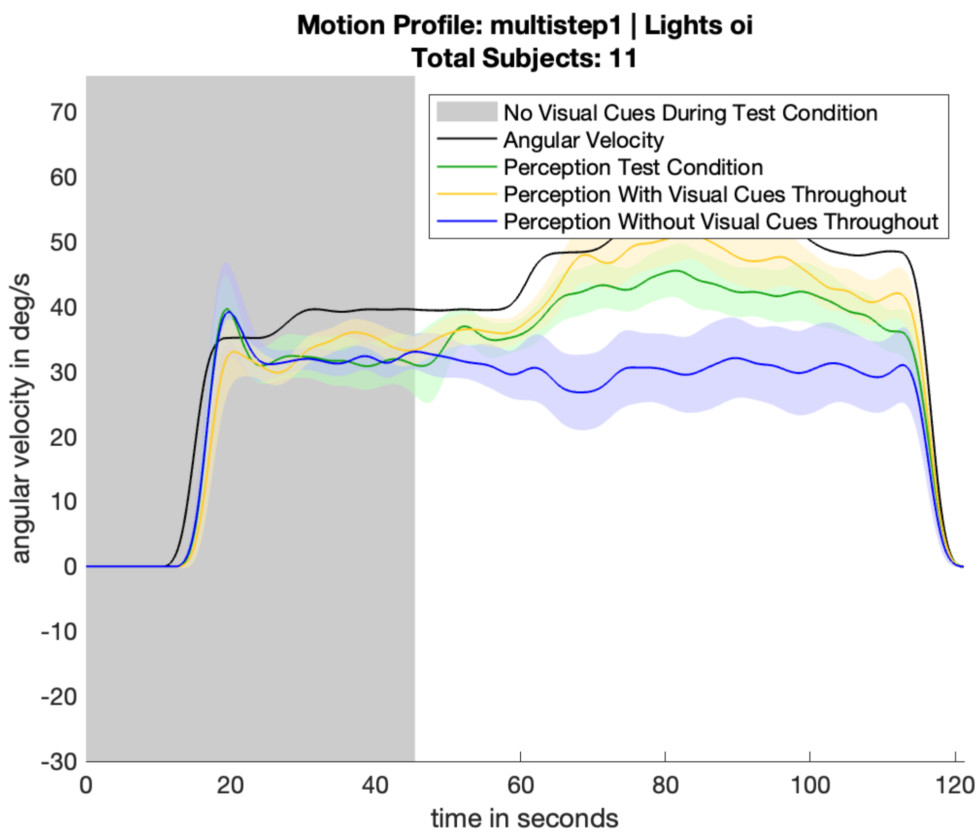
Motion Profile: multistep1 | Lights oi
Total Subjects: 11
No Visual Cues During Test Condition
Angular Velocity
Perception Test Condition
Perception With Visual Cues Throughout
Perception Without Visual Cues Throughout
angular velocity in deg/s
time in seconds
70
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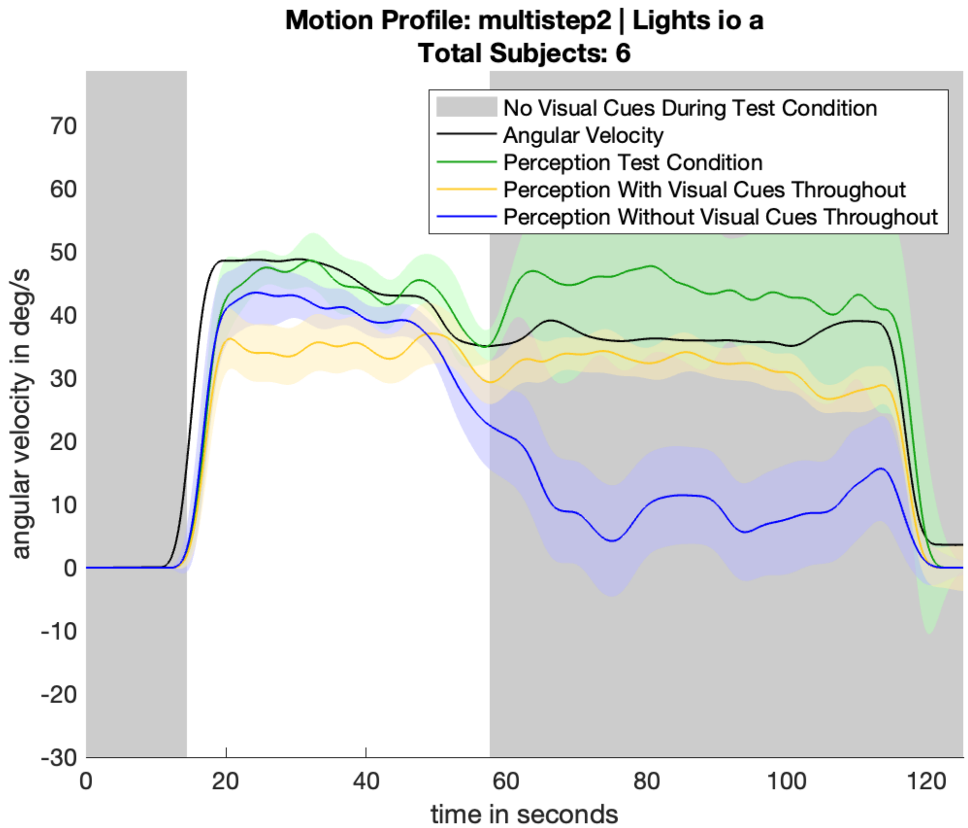
Motion Profile: multistep2 | Lights io a
Total Subjects: 6
No Visual Cues During Test Condition
Angular Velocity
Perception Test Condition
Perception With Visual Cues Throughout
Perception Without Visual Cues Throughout
angular velocity in deg/s
time in seconds
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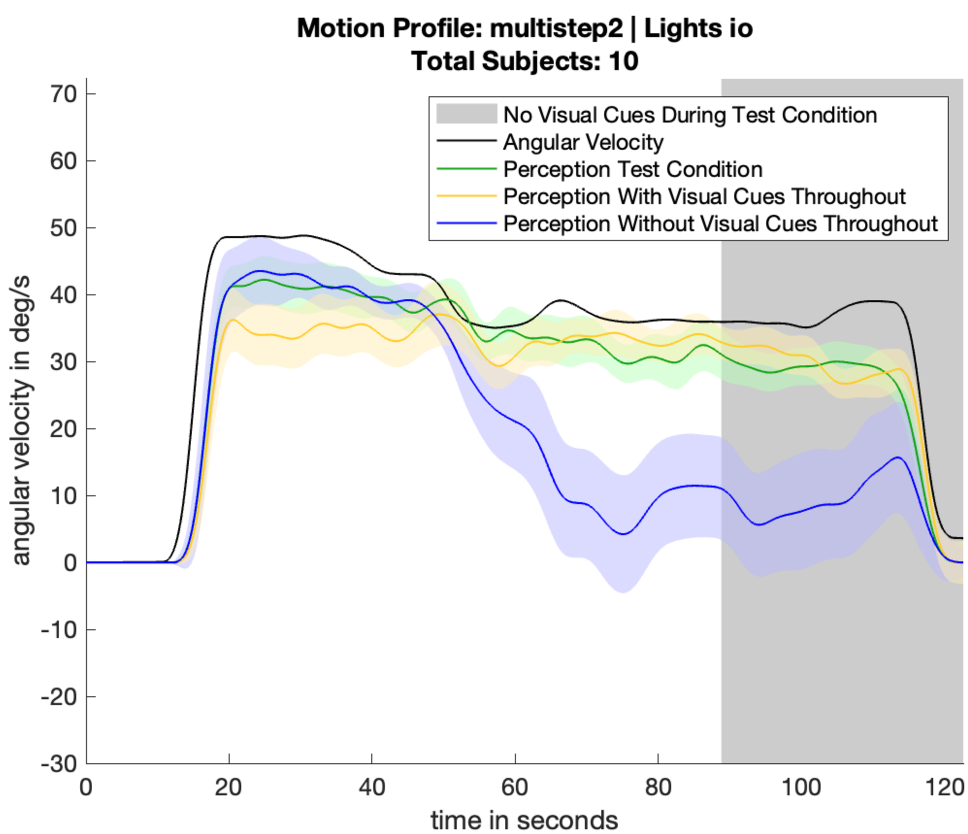
Motion Profile: multistep2 | Lights io
Total Subjects: 10
No Visual Cues During Test Condition
Angular Velocity
Perception Test Condition
Perception With Visual Cues Throughout
Perception Without Visual Cues Throughout
angular velocity in deg/s
time in seconds
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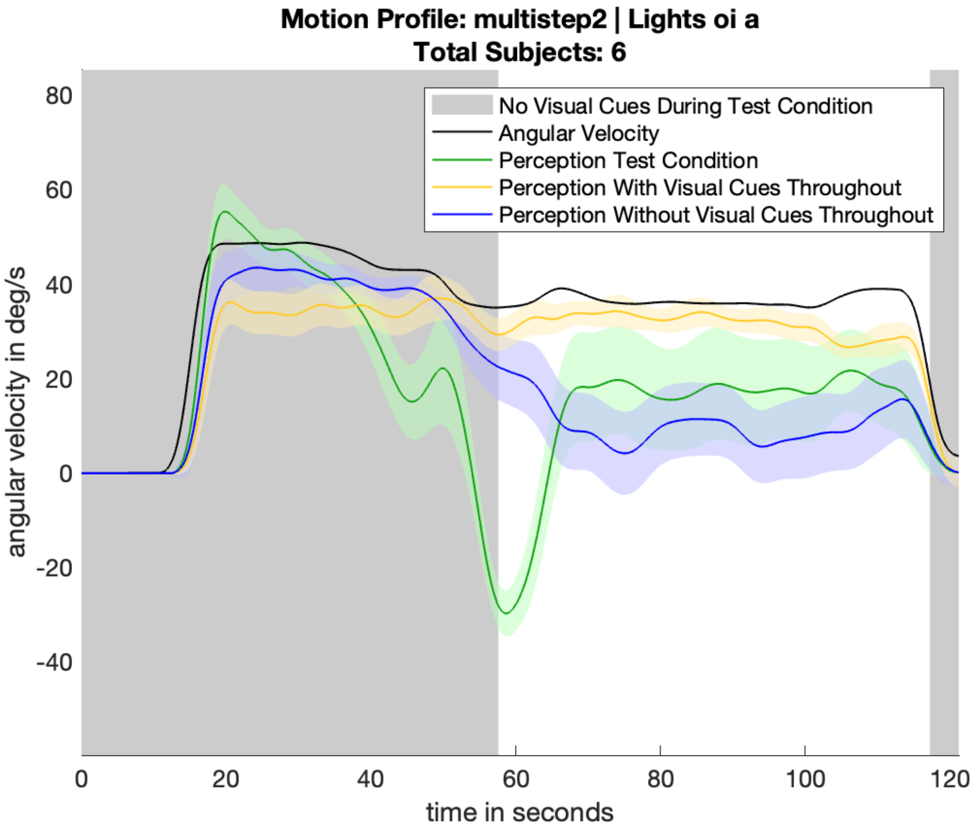
Motion Profile: multistep2 | Lights oi a
Total Subjects: 6
No Visual Cues During Test Condition
Angular Velocity
Perception Test Condition
Perception With Visual Cues Throughout
Perception Without Visual Cues Throughout
angular velocity in deg/s
time in seconds
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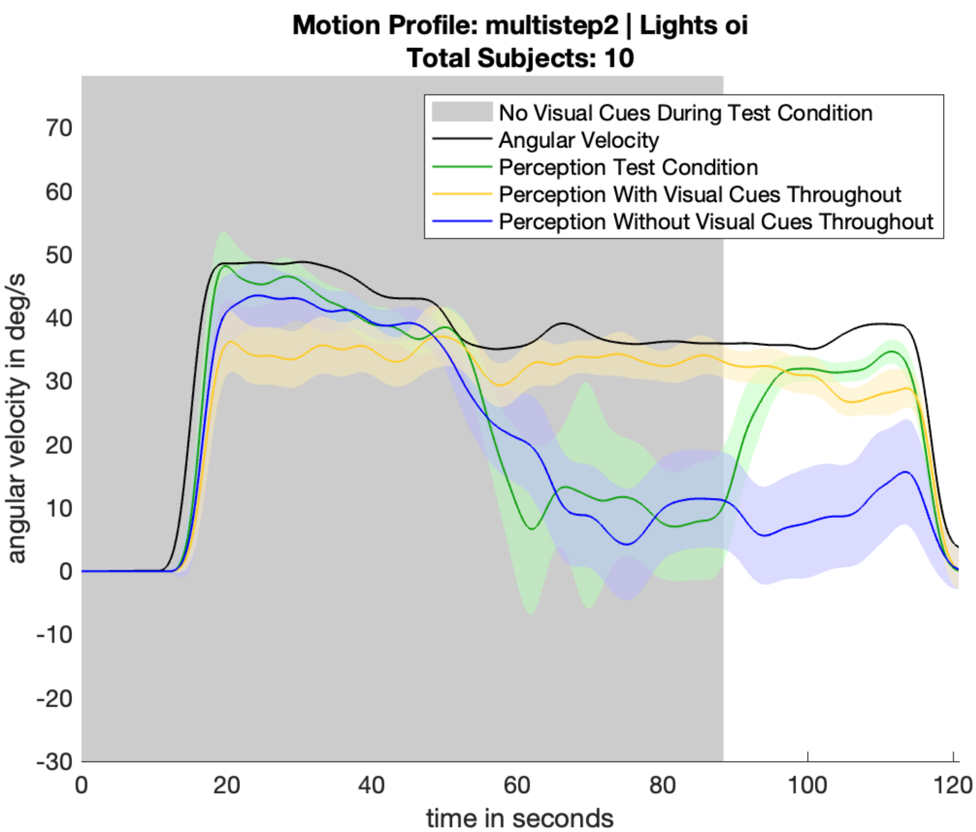
Motion Profile: multistep2 | Lights oi
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No Visual Cues During Test Condition
Angular Velocity
Perception Test Condition
Perception With Visual Cues Throughout
Perception Without Visual Cues Throughout
angular velocity in deg/s
time in seconds
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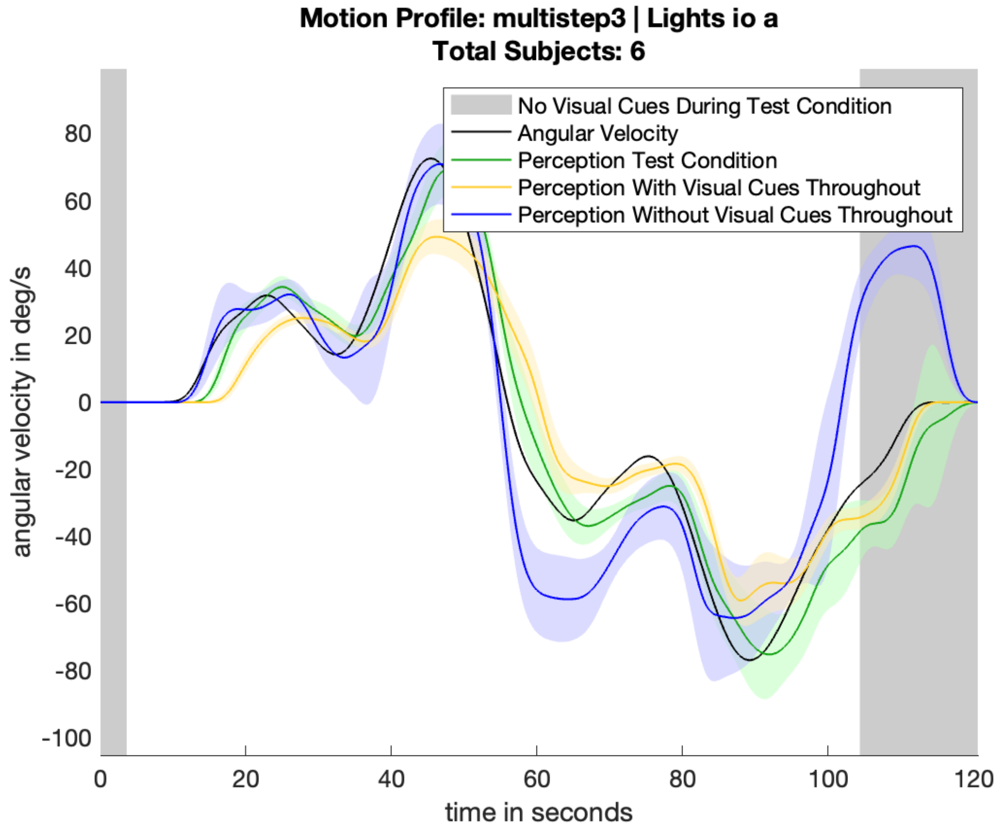
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Total Subjects: 6
No Visual Cues During Test Condition
Angular Velocity
Perception Test Condition
Perception With Visual Cues Throughout
Perception Without Visual Cues Throughout
angular velocity in deg/s
time in seconds
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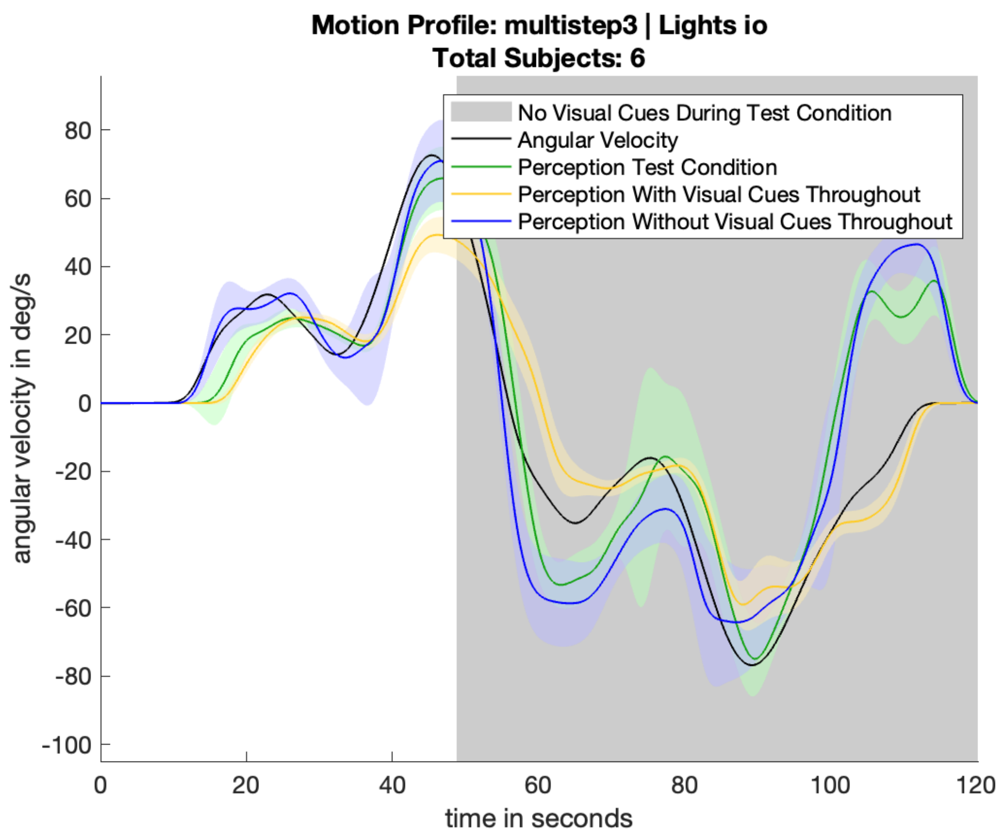
Motion Profile: multistep3 | Lights io
Total Subjects: 6
No Visual Cues During Test Condition
Angular Velocity
Perception Test Condition
Perception With Visual Cues Throughout
Perception Without Visual Cues Throughout
angular velocity in deg/s
time in seconds
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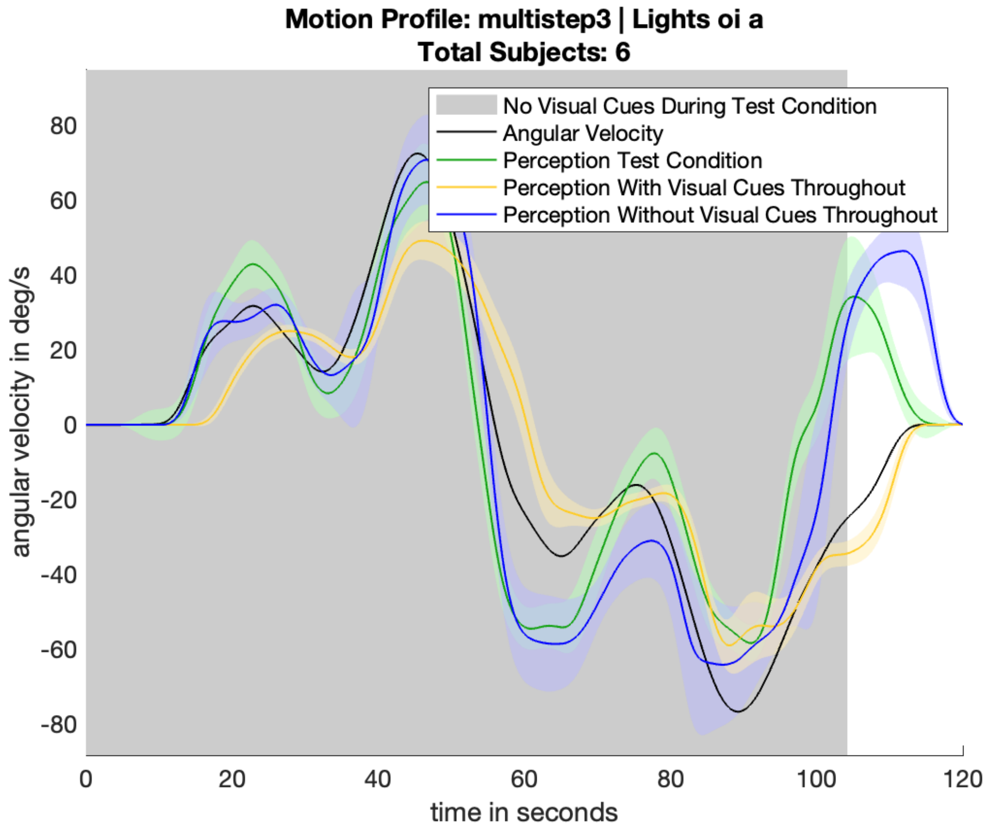
Motion Profile: multistep3 | Lights oi a
Total Subjects: 6
No Visual Cues During Test Condition
Angular Velocity
Perception Test Condition
Perception With Visual Cues Throughout
Perception Without Visual Cues Throughout
angular velocity in deg/s
time in seconds
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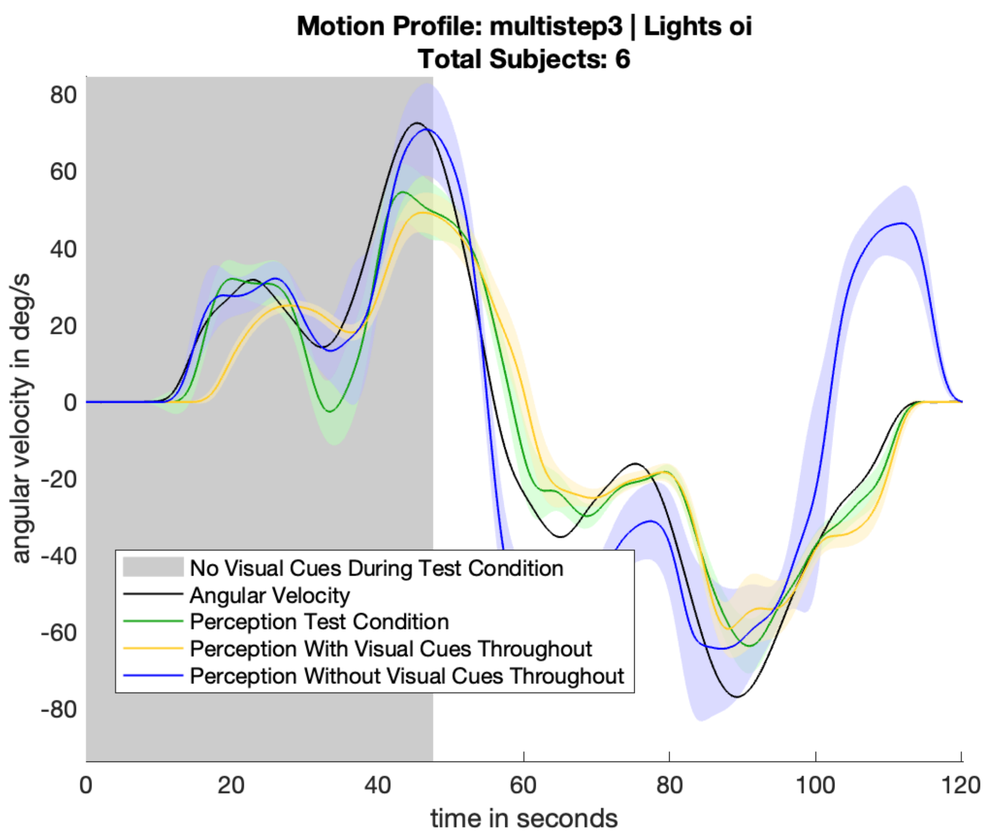
Motion Profile: multistep3 | Lights oi
Total Subjects: 6
No Visual Cues During Test Condition
Angular Velocity
Perception Test Condition
Perception With Visual Cues Throughout
Perception Without Visual Cues Throughout
angular velocity in deg/s
time in seconds
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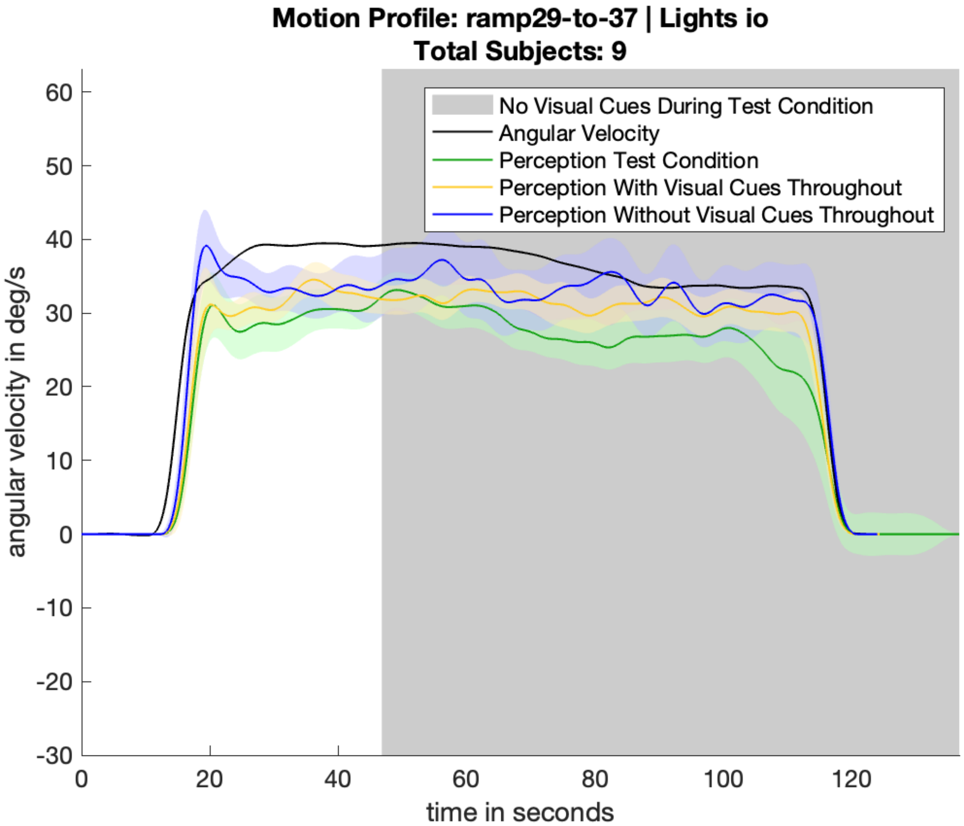
Motion Profile: ramp29-to-37 | Lights io
Total Subjects: 9
No Visual Cues During Test Condition
Angular Velocity
Perception Test Condition
Perception With Visual Cues Throughout
Perception Without Visual Cues Throughout
angular velocity in deg/s
time in seconds
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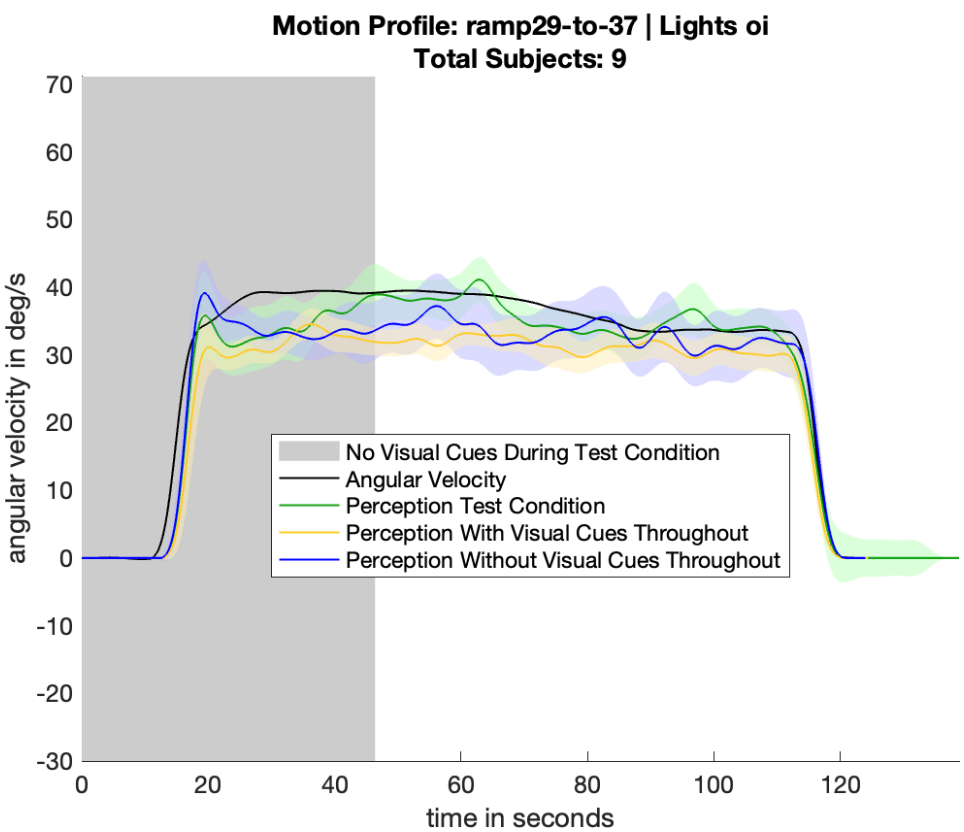
Motion Profile: ramp29-to-37 | Lights oi
Total Subjects: 9
No Visual Cues During Test Condition
Angular Velocity
Perception Test Condition
Perception With Visual Cues Throughout
Perception Without Visual Cues Throughout
angular velocity in deg/s
time in seconds
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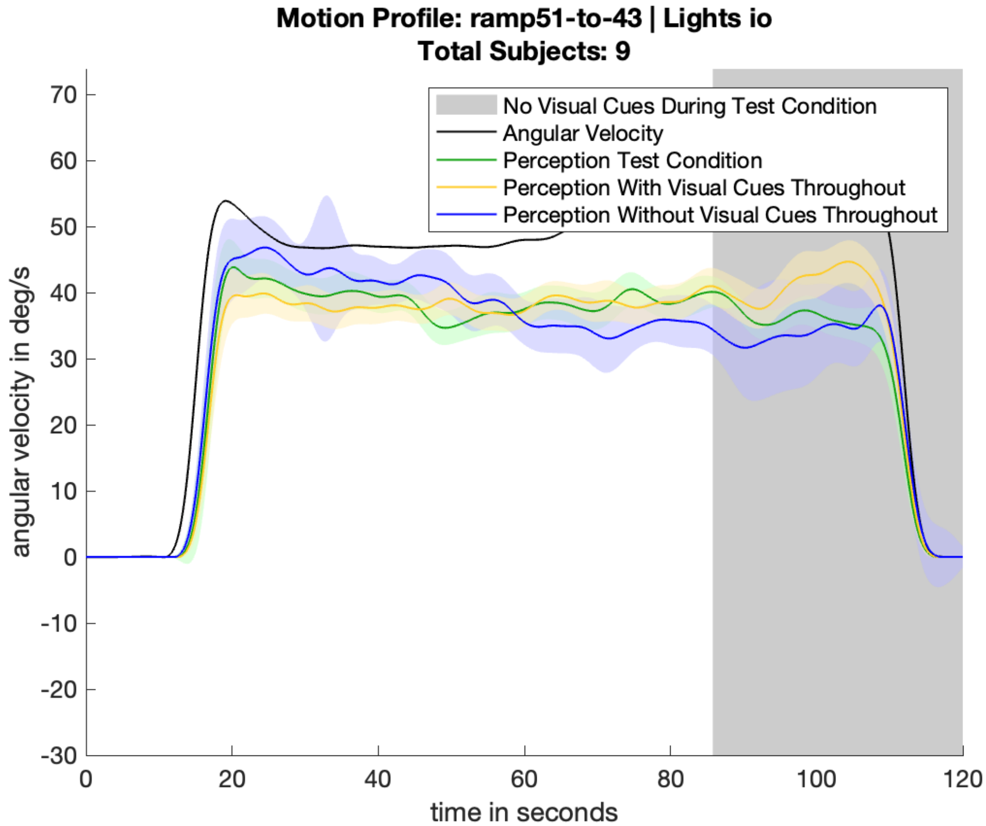
Motion Profile: ramp51-to-43 | Lights io
Total Subjects: 9
No Visual Cues During Test Condition
Angular Velocity
Perception Test Condition
Perception With Visual Cues Throughout
Perception Without Visual Cues Throughout
angular velocity in deg/s
time in seconds
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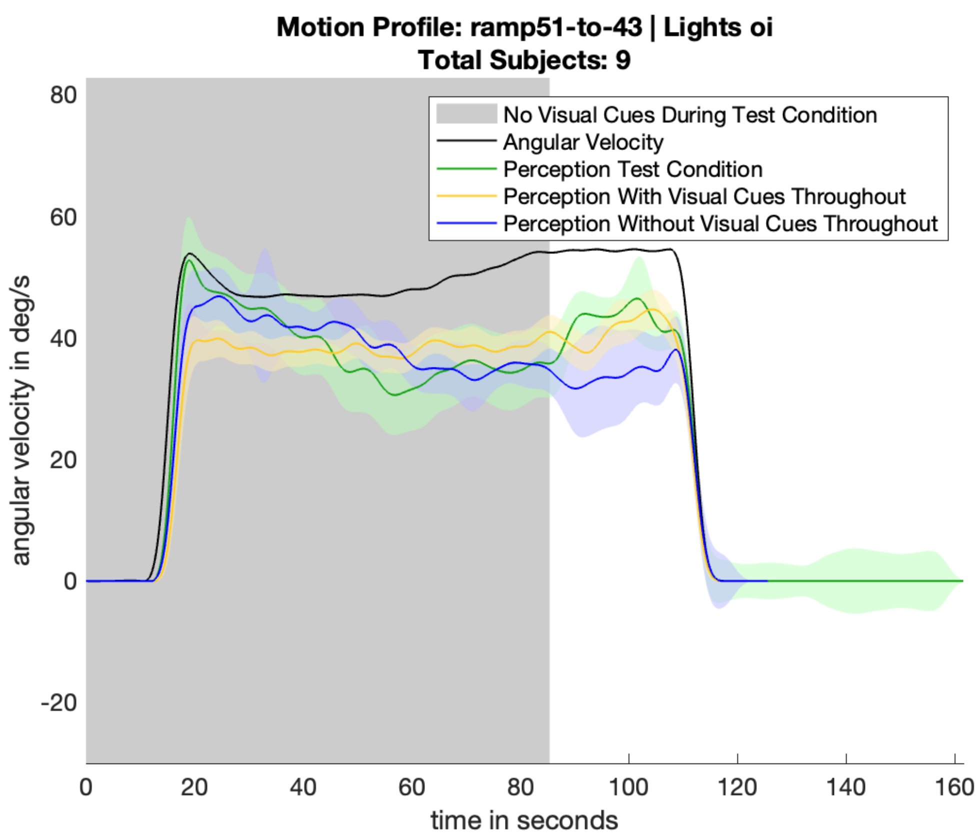
Motion Profile: ramp51-to-43 | Lights oi
Total Subjects: 9
No Visual Cues During Test Condition
Angular Velocity
Perception Test Condition
Perception With Visual Cues Throughout
Perception Without Visual Cues Throughout
angular velocity in deg/s
time in seconds
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Appendix B

Additional Data within Specific Aim Two

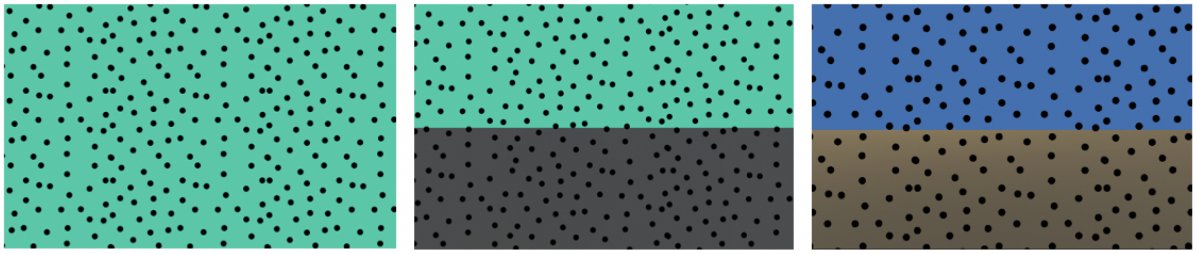
Similar to occurrences in Specific Aim One, I collected more data than is presented in Specific Aim Two as well. The unpresented data from Specific Aim Two, however was collected under the influence of different visual scenes as opposed to different motion profiles (used in Specific Aim One).

B.1 Additional Visual Scenes

In Specific Aim Two I present data on tilt perception with visual cues that stimulate the visual verticality and visual angular velocity pathways. In addition, I collected tilt perception data with the same motion profiles but with two additional different visual scenes. The three visual scenes are shown in Figure B.1. One visual scene (left) had dots that would rotate only (they would not translate even if the subject was translating). One visual scene had dots and a horizon that would rotate but not translate even if the subject was translating (center). This is the only visual scene presented in the main body of this thesis. The final visual scene had dots that would rotate and translate as well as a horizon that would rotate (right).

I collected additional tilt data under the influence of a visual scene that stimulated only the visual angular velocity pathway and of a visual scene that stimulated the visual linear velocity, visual angular velocity, and visual verticality pathways. The data presented in Aim Two was collected under the influence of a visual scene stimulating the visual angular velocity and visual verticality pathways.

Figure B.1: The three visual scenes used in Specific Aim Two.



B.2 Additional Visual Scene Findings

I noted that tilt perception with no visual cues and tilt perception under the influence of a visual scene stimulating the visual angular velocity pathway was not substantially different. This is shown in Figure B.2. At the small tilt angles used in Specific Aim Two, visual angular velocity cues alone were insufficient in generating accurate perceptions of tilt. Indeed, in the data I collected, I did not see substantial differences between tilt perception in the two control conditions when only visual angular velocity cues were provided. Figure B.3 depicts an example of where the data between the two control conditions was not substantially different when the visual cues provided only stimulated the visual angular velocity pathway. This is why I initially hypothesized that filtering in the visual verticality pathway would resolve the gradual integration of a sudden visual cue availability change.

I chose not to present the additional data collected during Specific Aim 2 in the main body of the thesis because the data with one of the three visual scenes I collected was sufficient to meet the goals of the aim. Ultimately, while additional data exists, I deemed it unnecessarily confusing to include.

B.3 Additional Data and Final Notes

All data collected in Specific Aim Two is shown in the following pages. No additional data exists for Specific Aim Three. Everything collected in Specific Aim Three is presented in the main

Figure B.2: Observer model predictions of tilt perception with and without visual angular velocity cues.

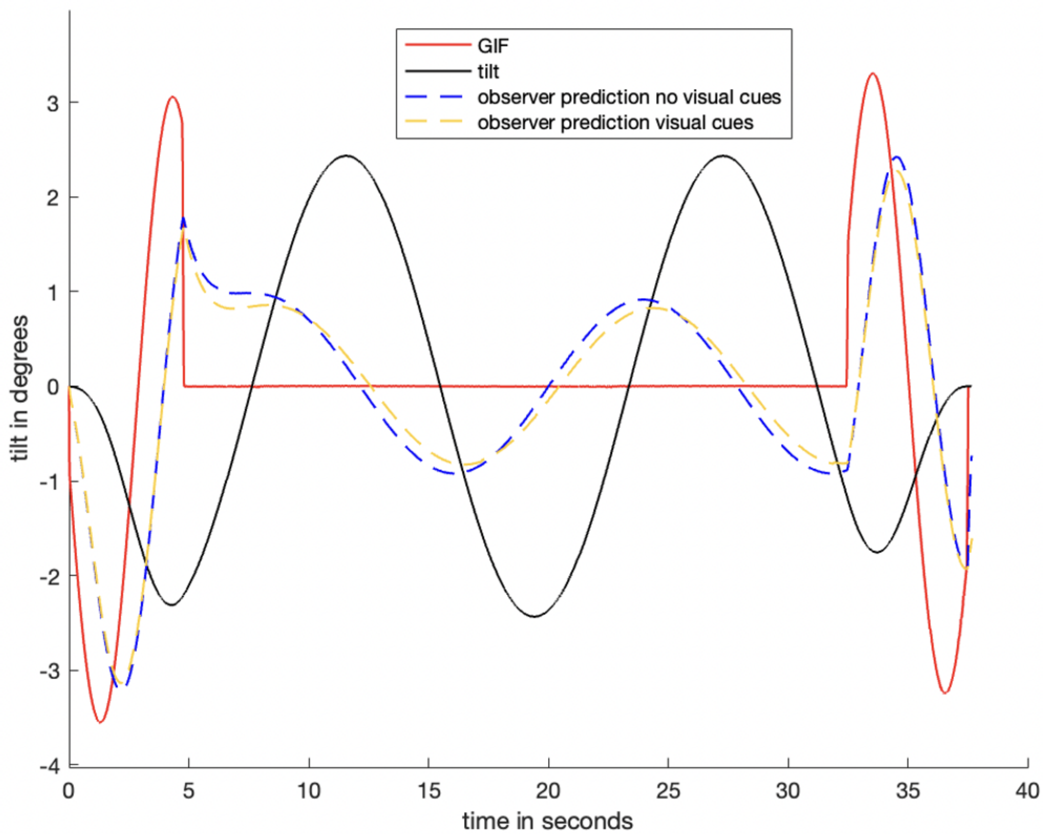
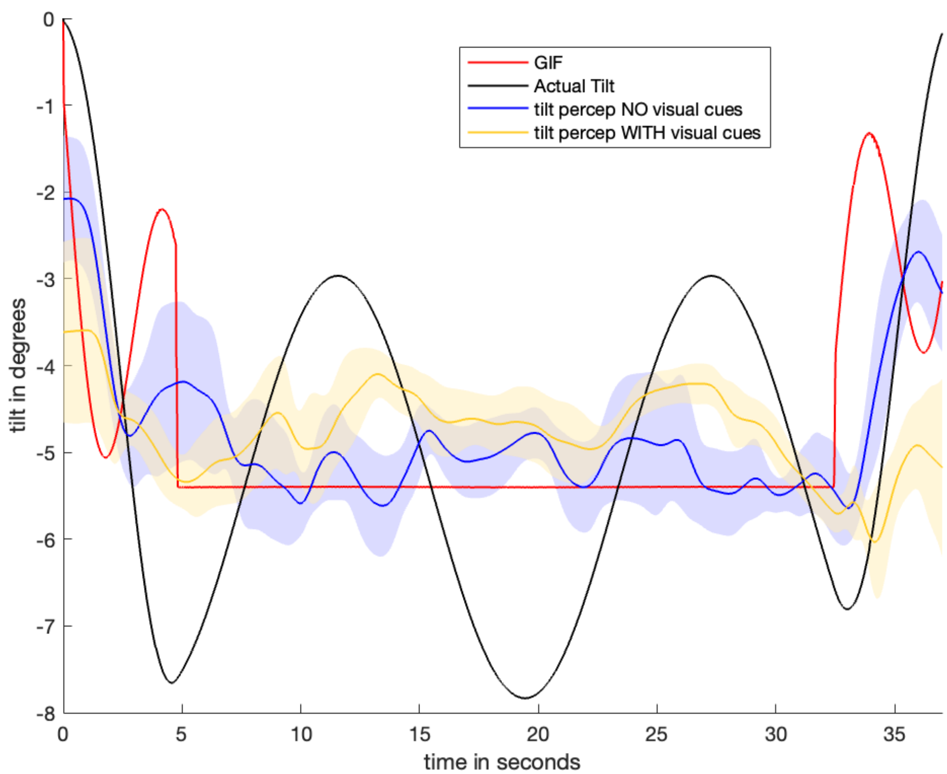
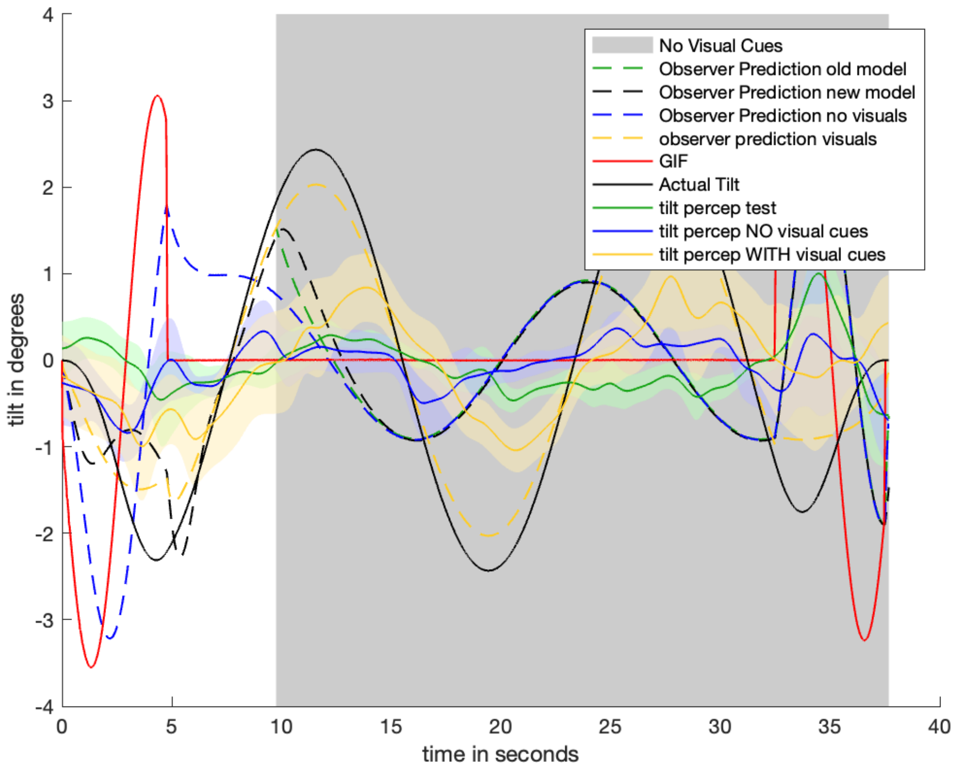


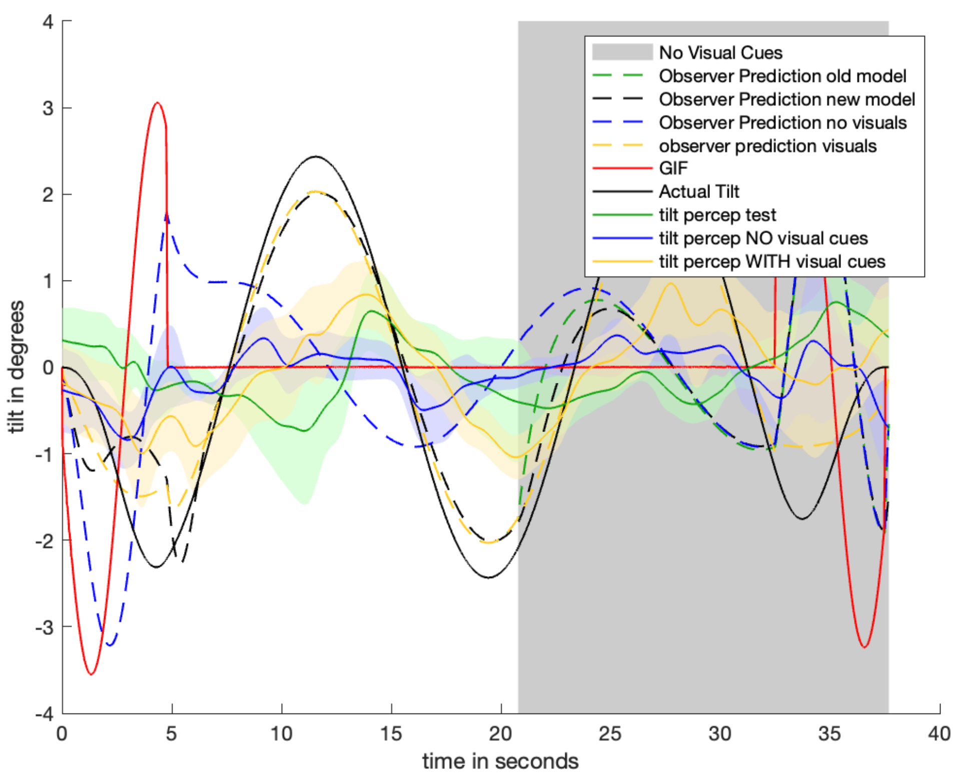
Figure B.3: Unpresented data in which there was little difference between the two control conditions.

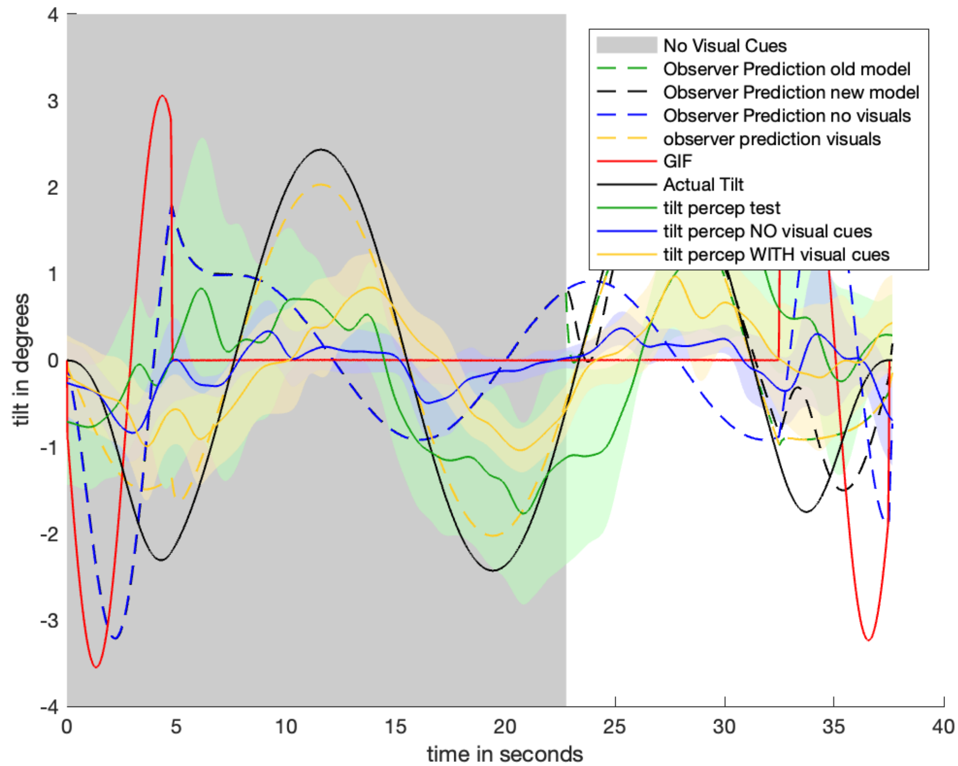


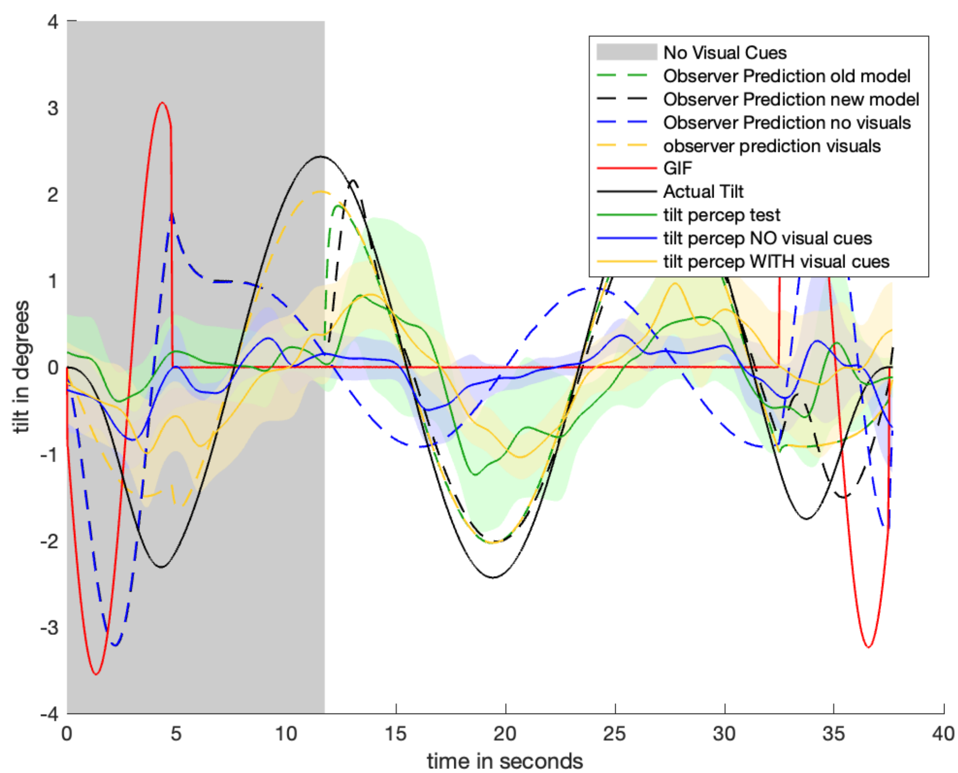
body of this thesis.

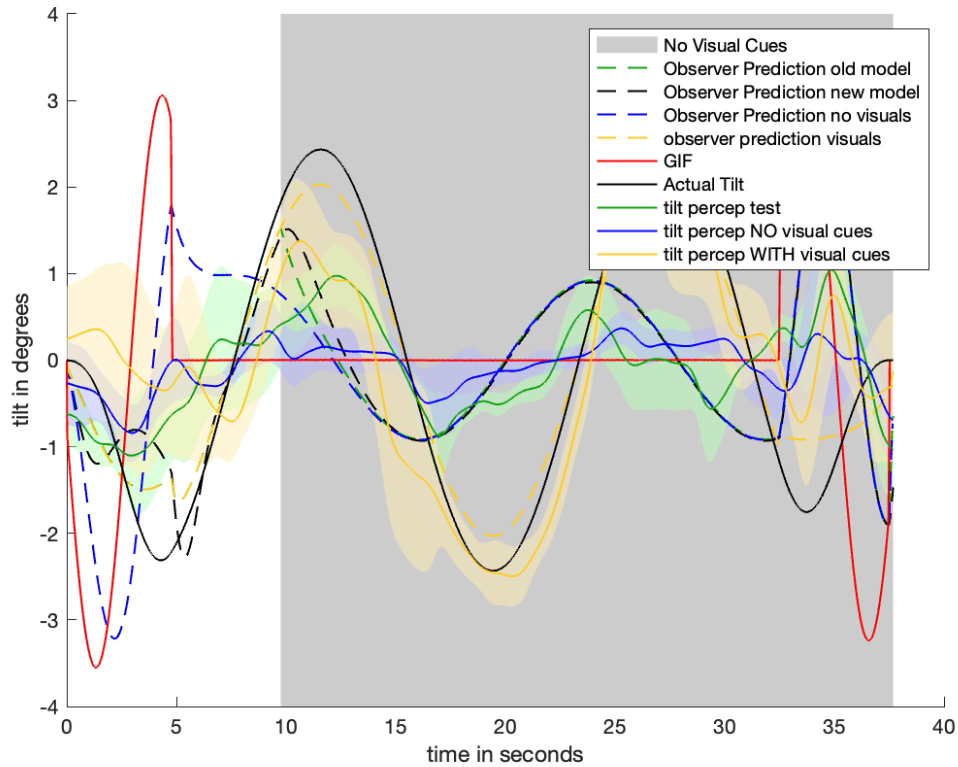
Figure B.4: The following pages (pp117 - pp130) include a group of figures indicating additional data collected in Specific Aim Two.


No Visual Cues
Observer Prediction old model
Observer Prediction new model
Observer Prediction no visuals
observer prediction visuals
GIF
Actual Tilt
tilt percep test
tilt percep NO visual cues
tilt percep WITH visual cues
tilt in degrees
time in seconds

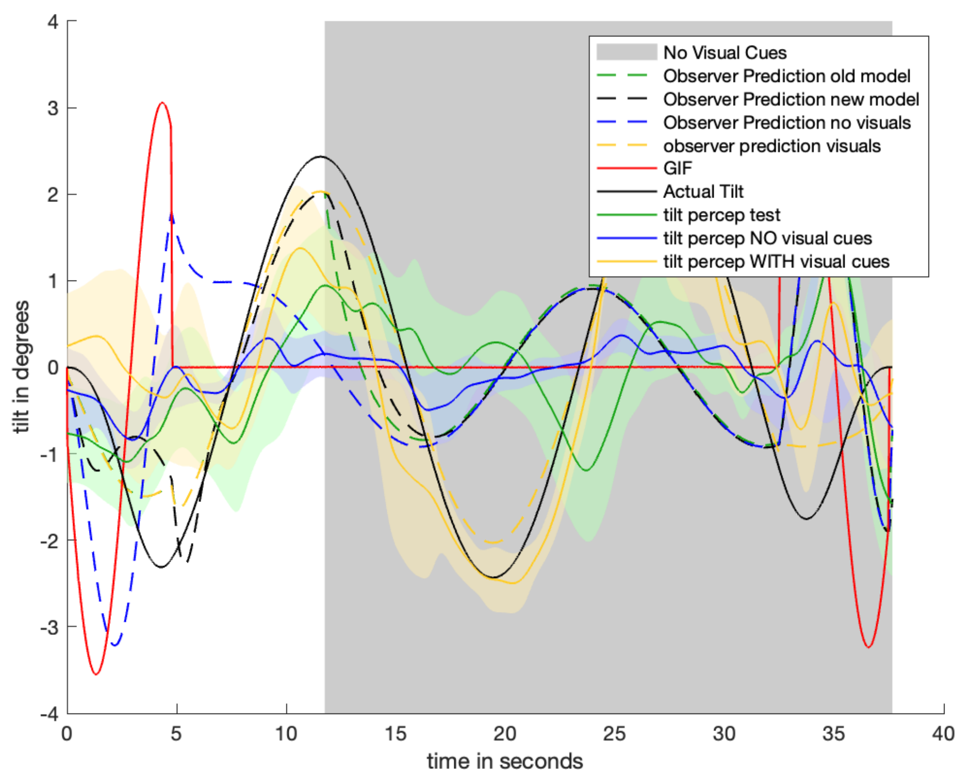

No Visual Cues
Observer Prediction old model
Observer Prediction new model
Observer Prediction no visuals
observer prediction visuals
GIF
Actual Tilt
tilt percep test
tilt percep NO visual cues
tilt percep WITH visual cues
tilt in degrees
time in seconds


No Visual Cues
Observer Prediction old model
Observer Prediction new model
Observer Prediction no visuals
observer prediction visuals
GIF
Actual Tilt
tilt percep test
tilt percep NO visual cues
tilt percep WITH visual cues
tilt in degrees
time in seconds

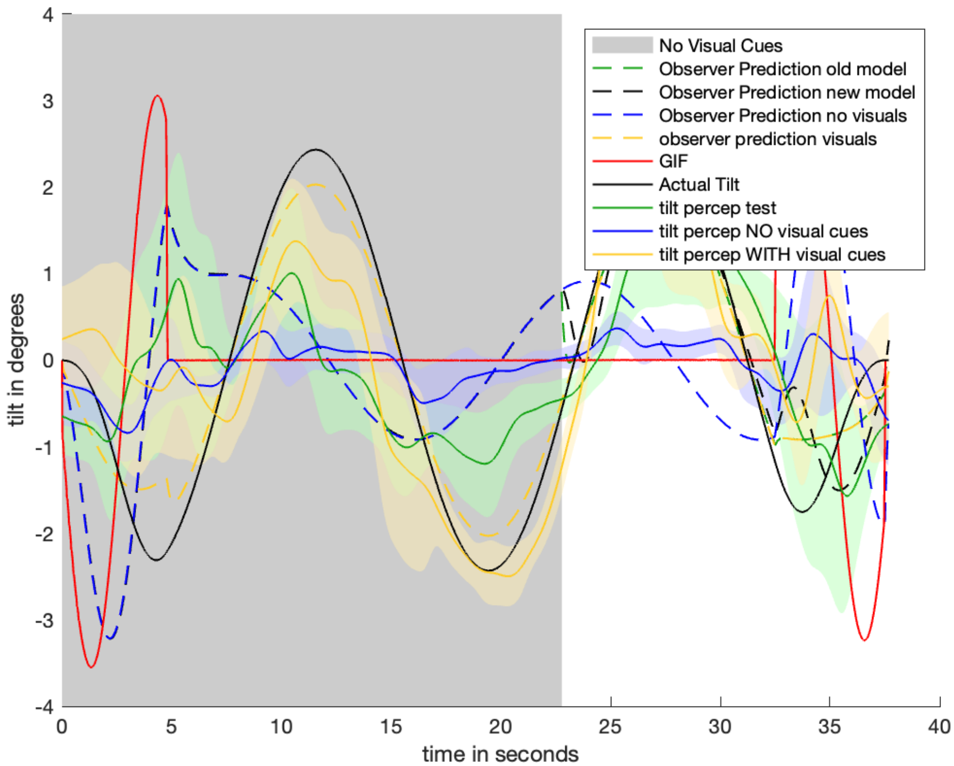

No Visual Cues
Observer Prediction old model
Observer Prediction new model
Observer Prediction no visuals
observer prediction visuals
GIF
Actual Tilt
tilt percep test
tilt percep NO visual cues
tilt percep WITH visual cues
tilt in degrees
time in seconds



No Visual Cues
Observer Prediction old model
Observer Prediction new model
Observer Prediction no visuals
observer prediction visuals
GIF
Actual Tilt
tilt percep test
tilt percep NO visual cues
tilt percep WITH visual cues
tilt in degrees
time in seconds



No Visual Cues
Observer Prediction old model
Observer Prediction new model
Observer Prediction no visuals
observer prediction visuals
GIF
Actual Tilt
tilt percep test
tilt percep NO visual cues
tilt percep WITH visual cues
tilt in degrees
time in seconds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Observer Prediction new model
Observer Prediction no visuals
observer prediction visuals
GIF
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tilt percep NO visual cues
tilt percep WITH visual cues
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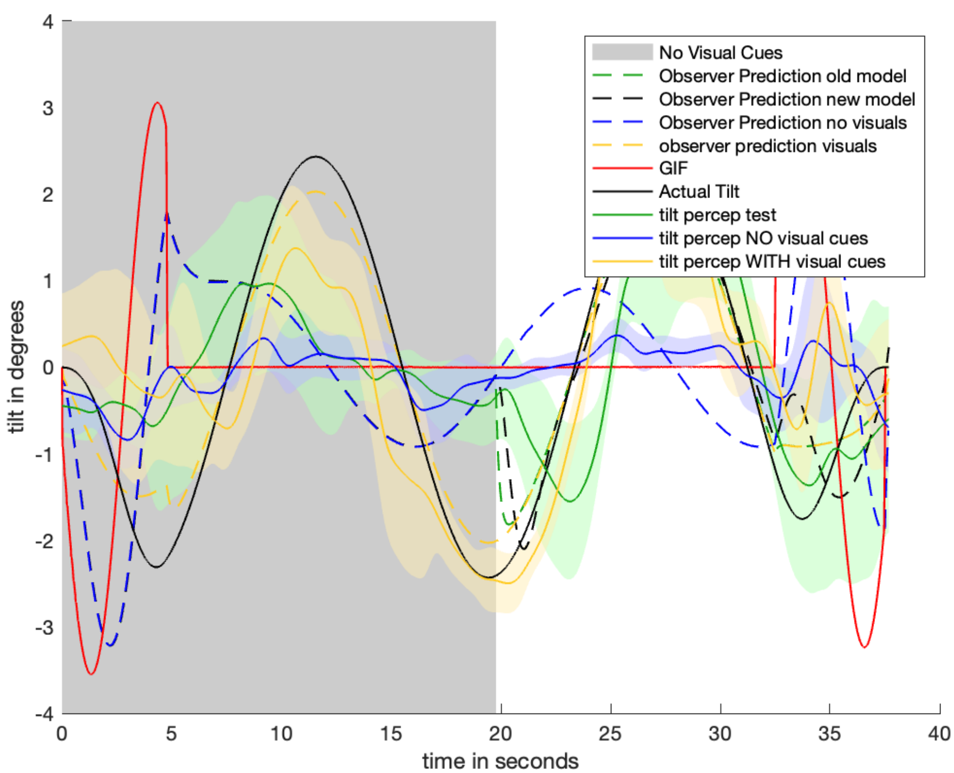
No Visual Cues
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Observer Prediction new model
Observer Prediction no visuals
observer prediction visuals
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tilt percep NO visual cues
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tilt in degrees
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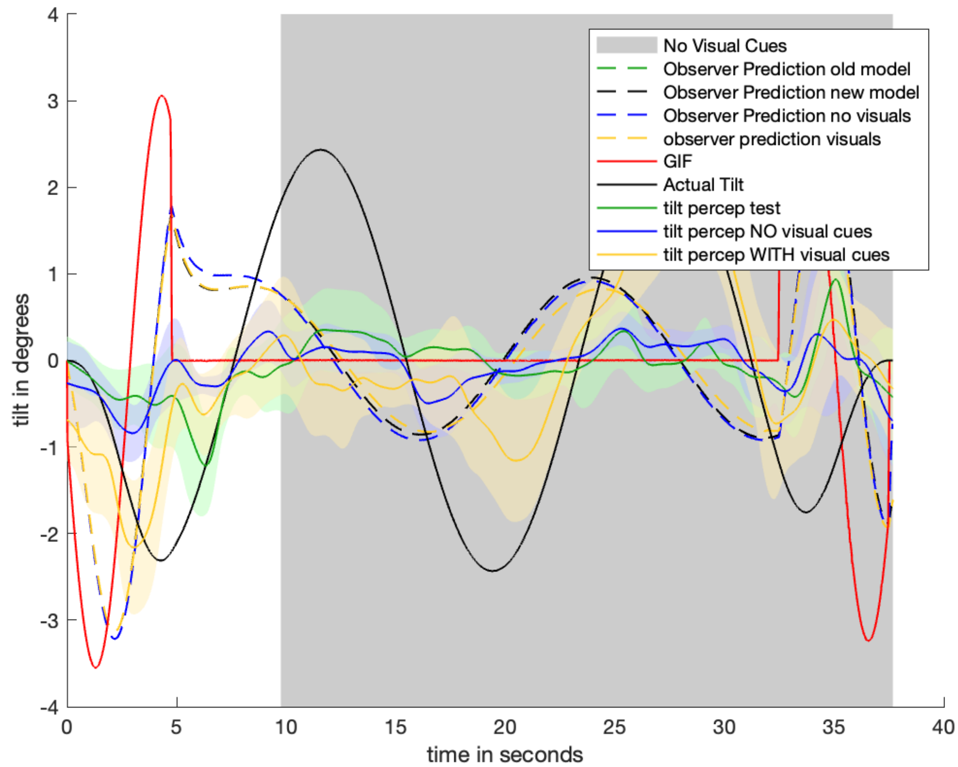
No Visual Cues
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Actual Tilt
tilt percep test
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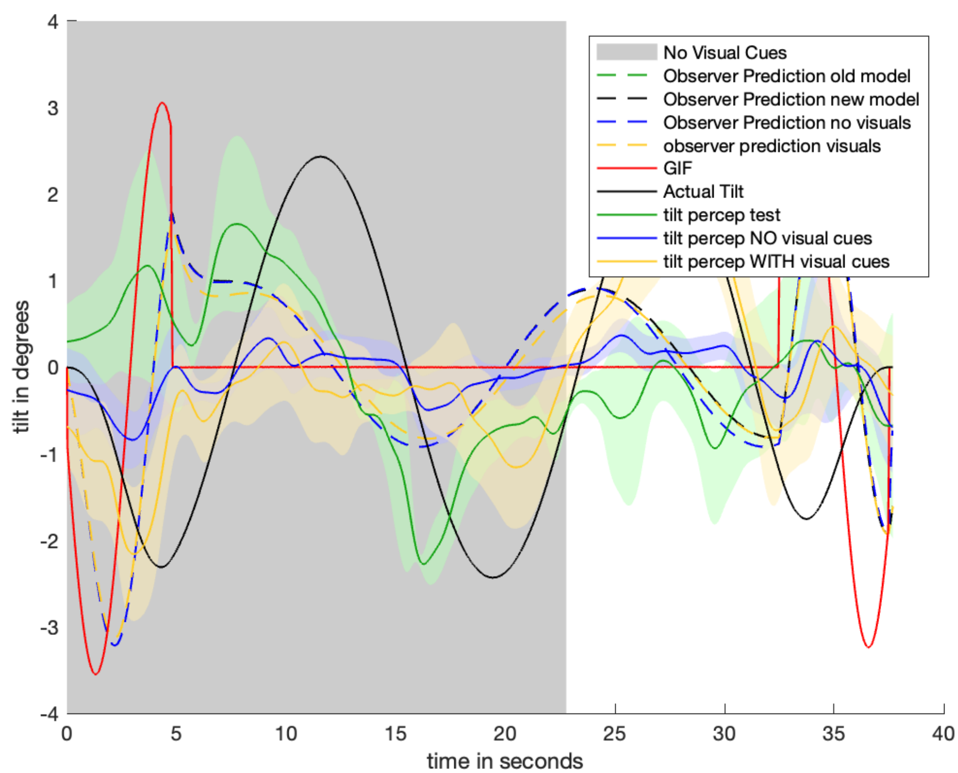
tilt percep WITH visual cues
tilt in degrees
time in seconds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Observer Prediction new model
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tilt percep test
tilt percep NO visual cues
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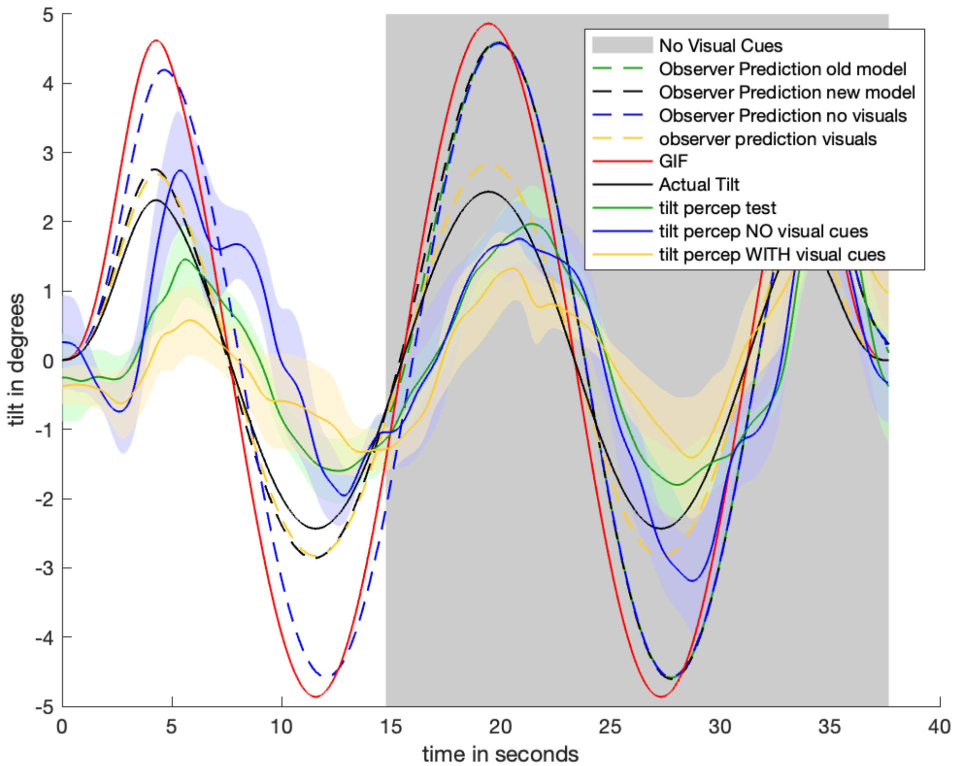
tilt in degrees
time in seconds


No Visual Cues
Observer Prediction old model
Observer Prediction new model
Observer Prediction no visuals
observer prediction visuals
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tilt percep test
tilt percep NO visual cues
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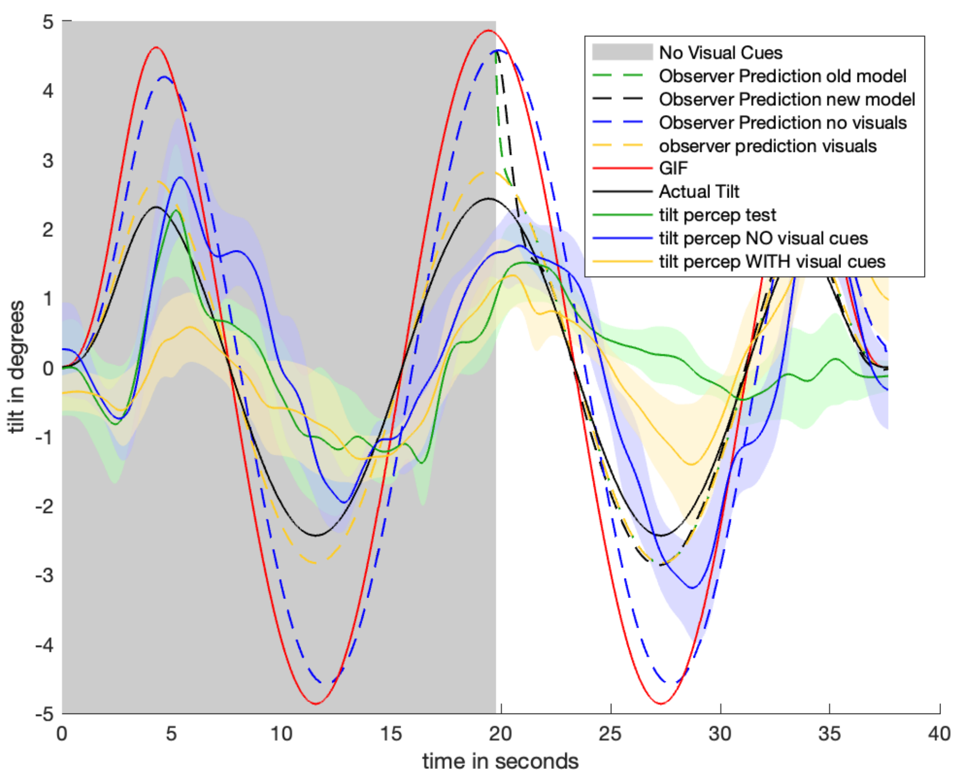
No Visual Cues
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Observer Prediction new model
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observer prediction visuals
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tilt percep NO visual cues
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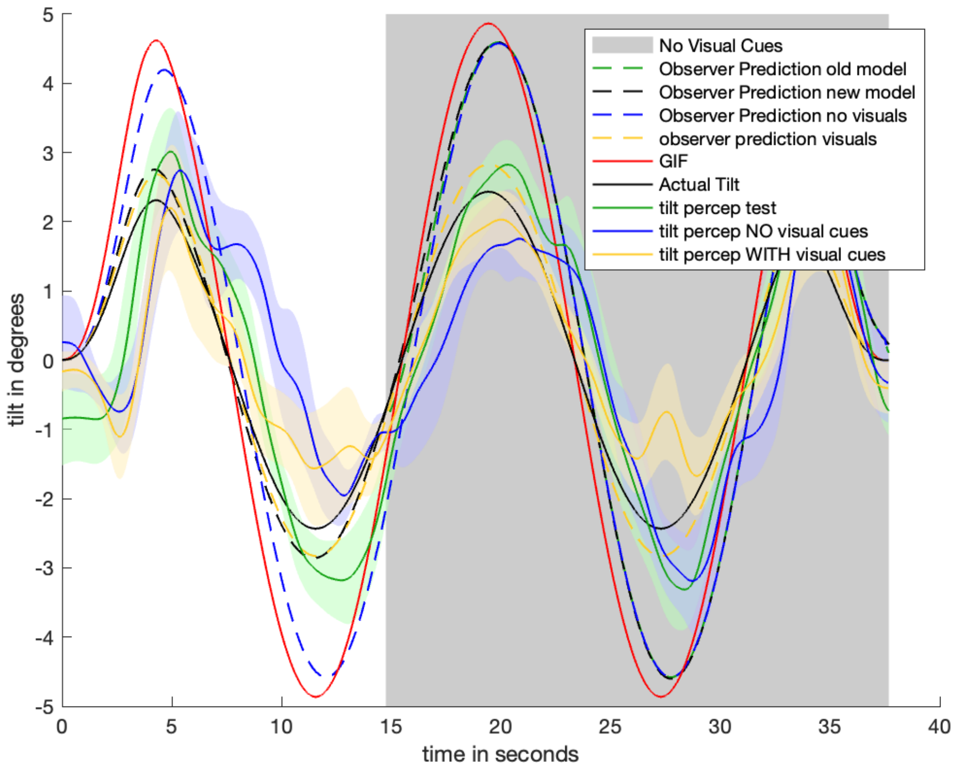
No Visual Cues
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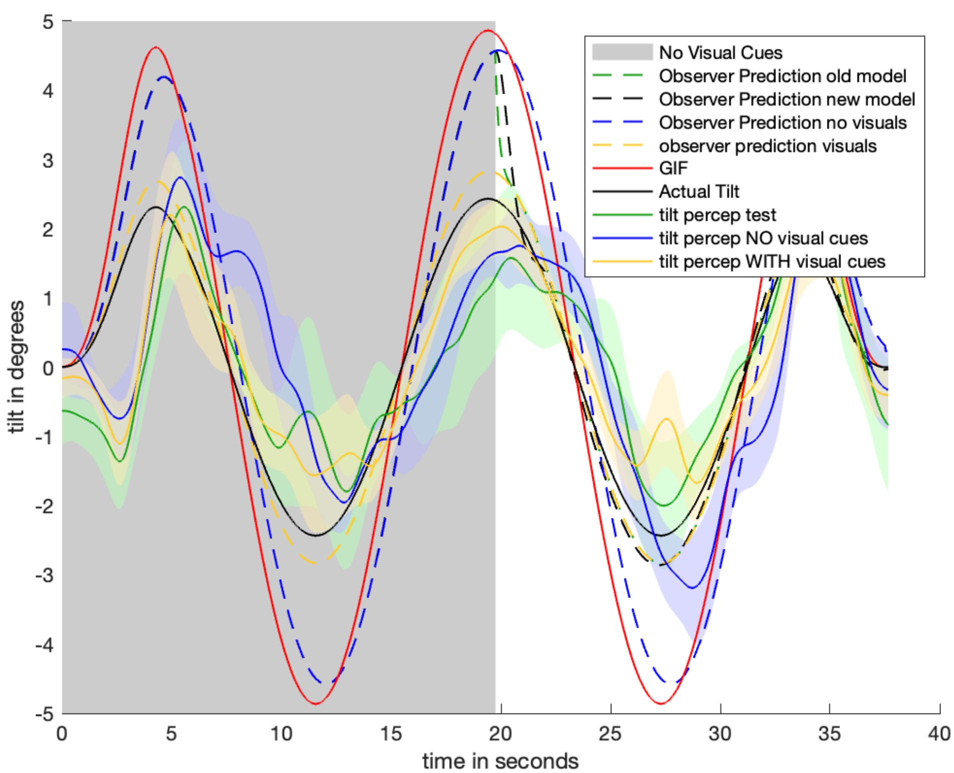
tilt percep WITH visual cues
tilt in degrees
time in seconds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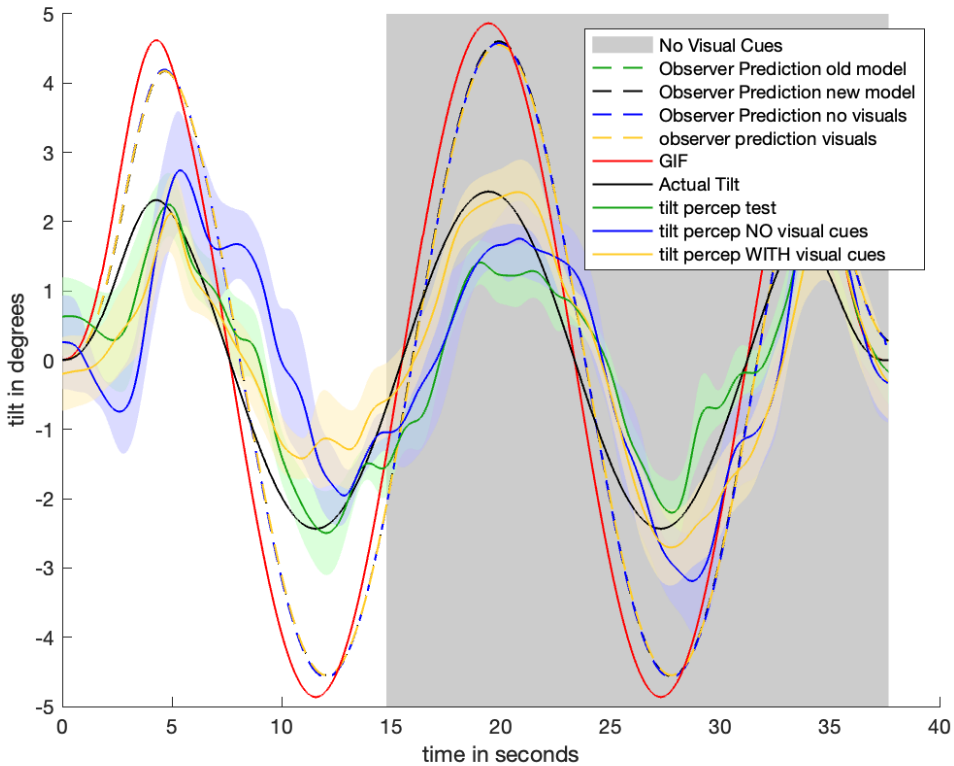
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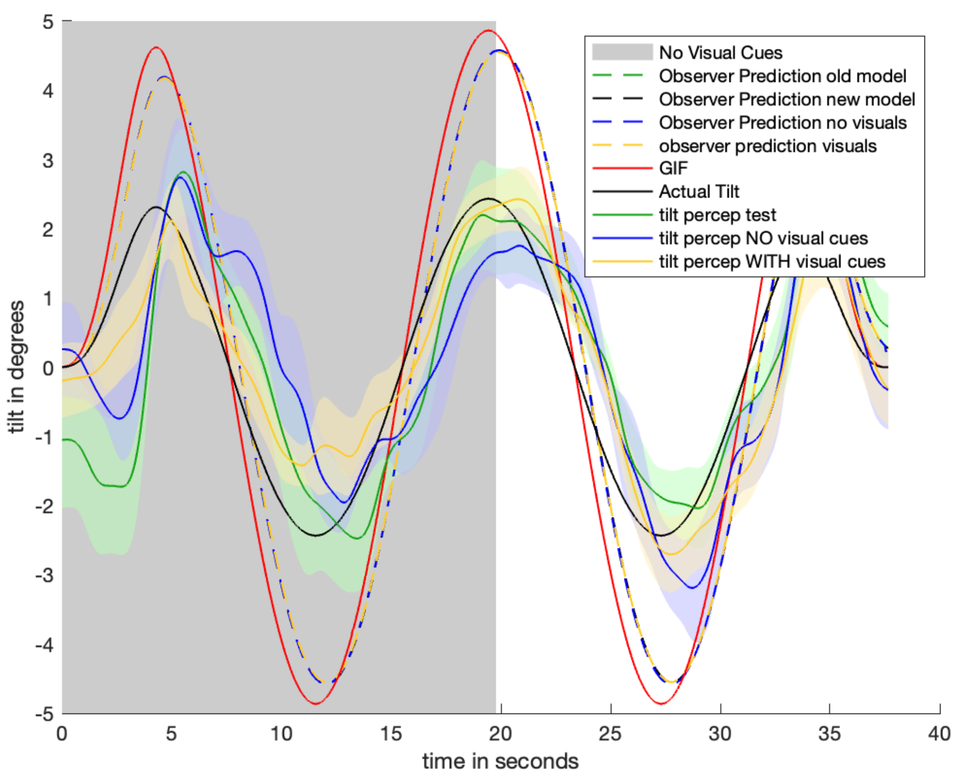
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Observer Prediction new model
Observer Prediction no visuals
observer prediction visuals
GIF
Actual Tilt
tilt percep test
tilt percep NO visual cues
tilt percep WITH visual cues
tilt in degrees
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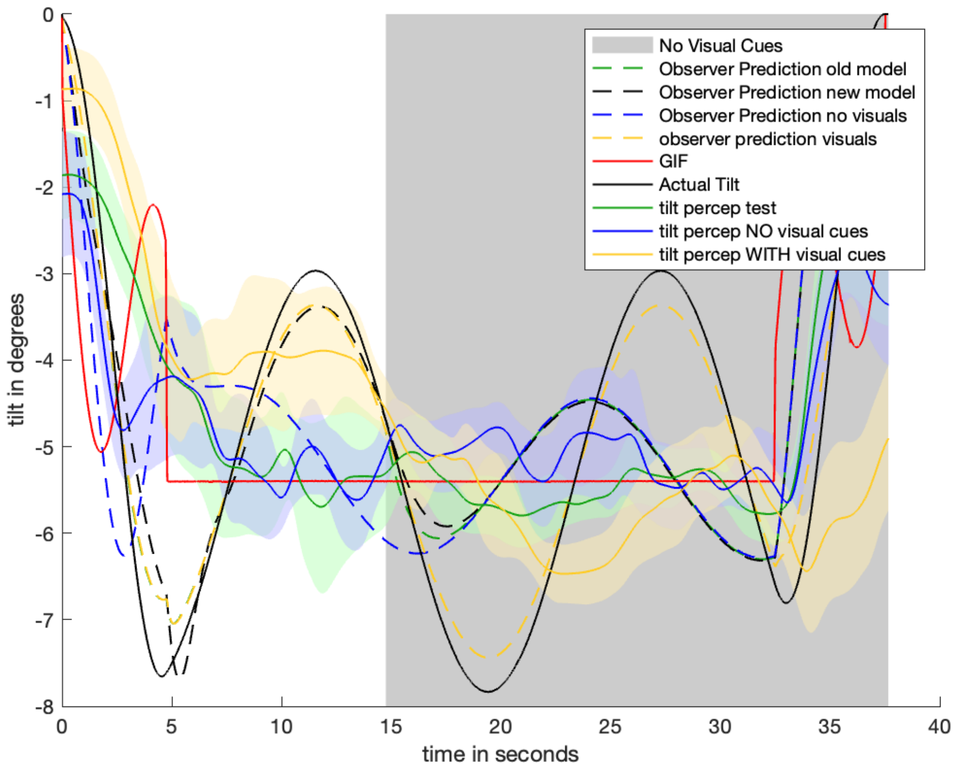
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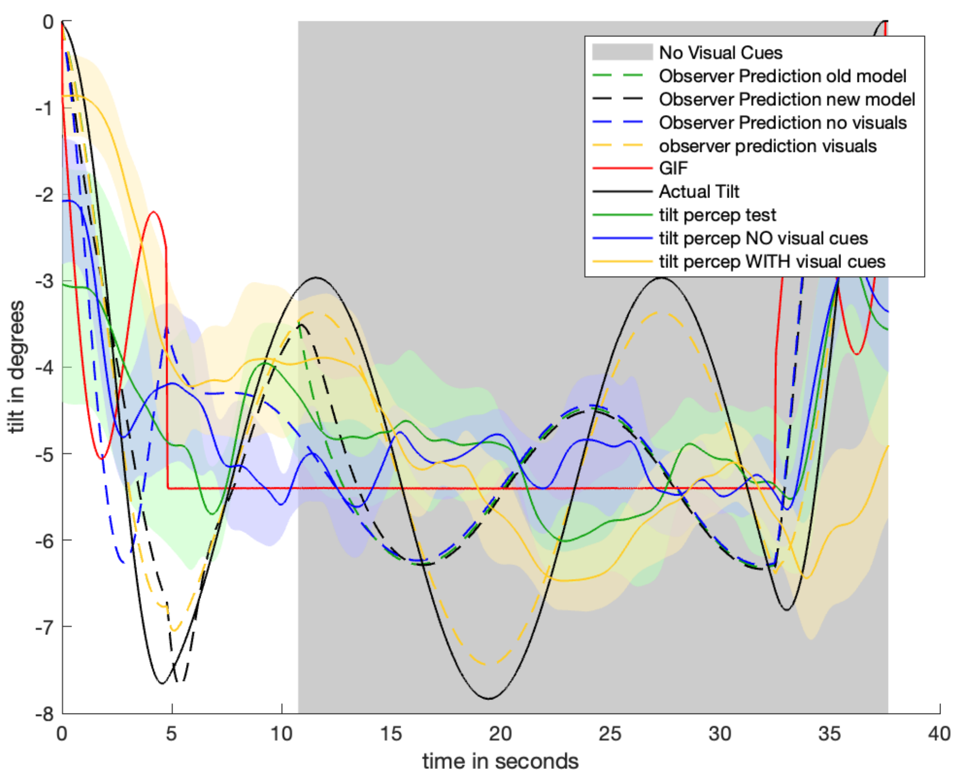
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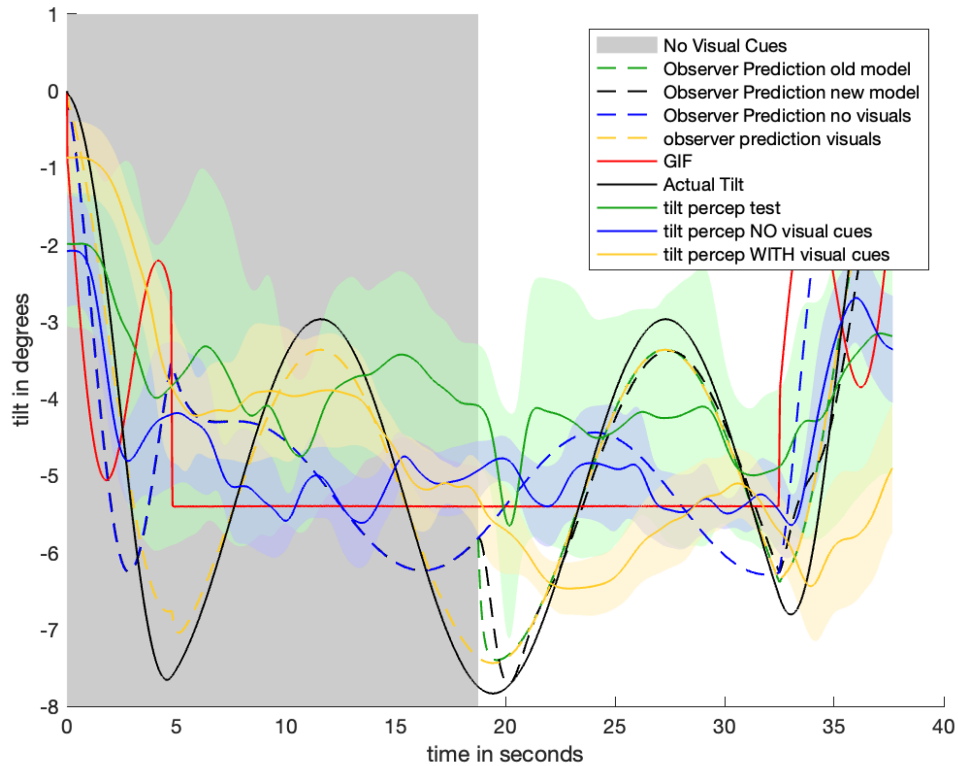
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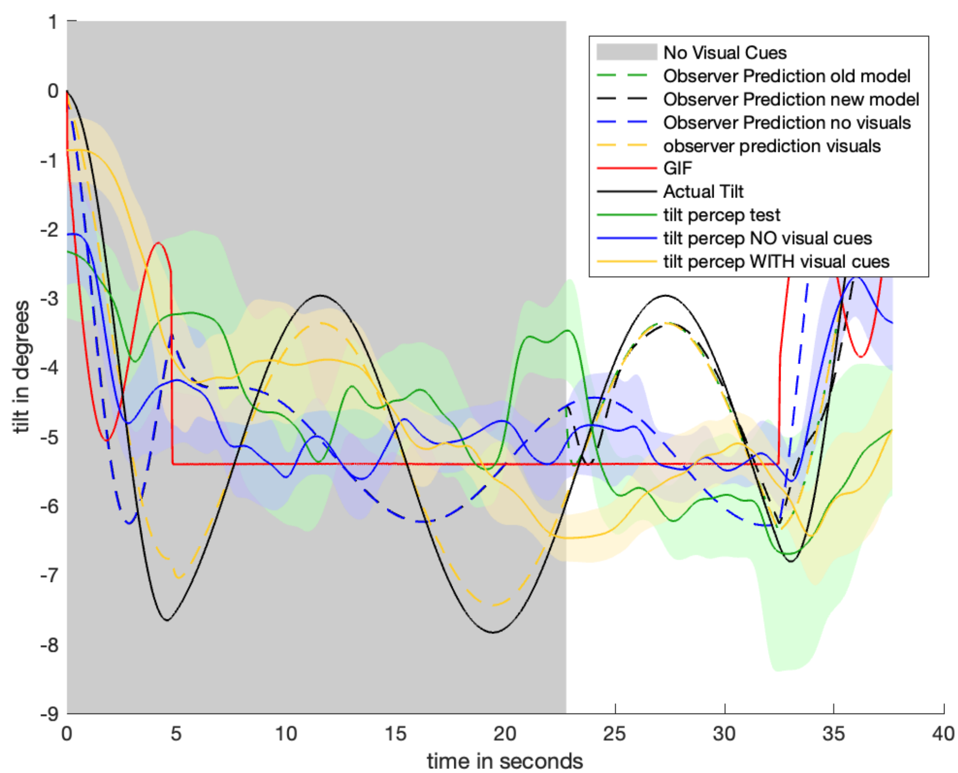
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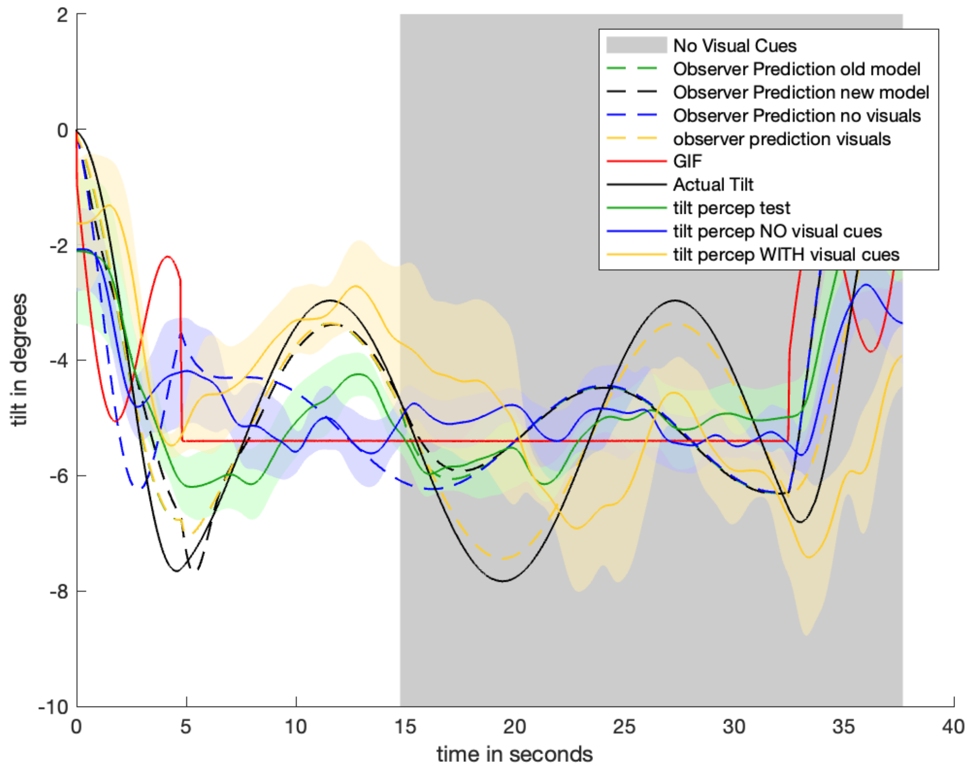
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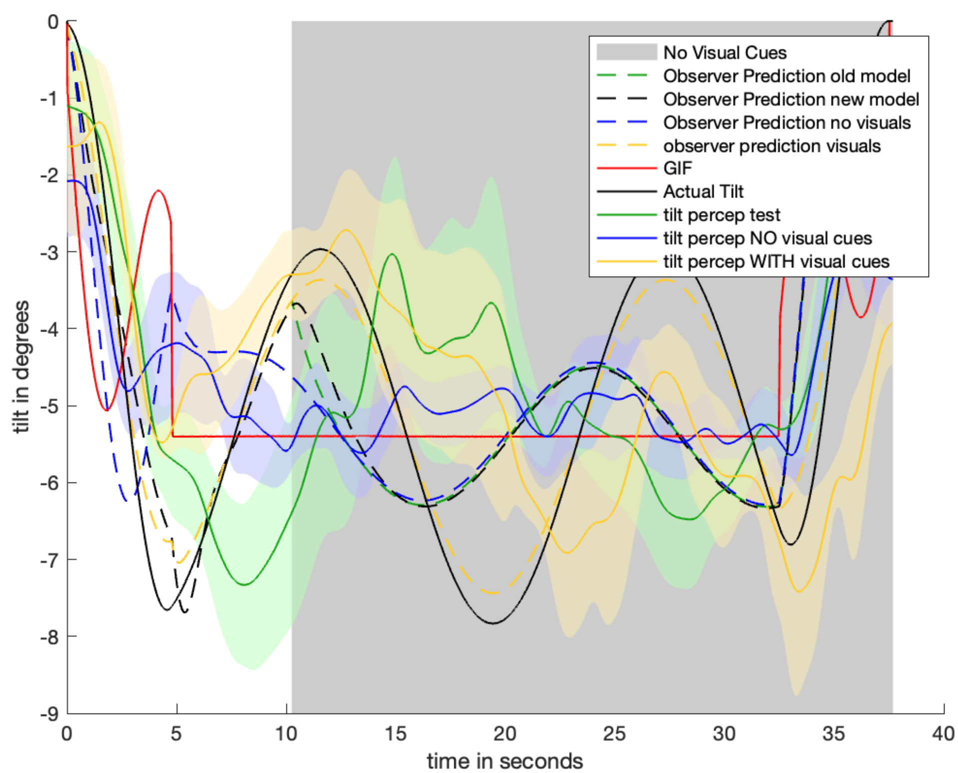
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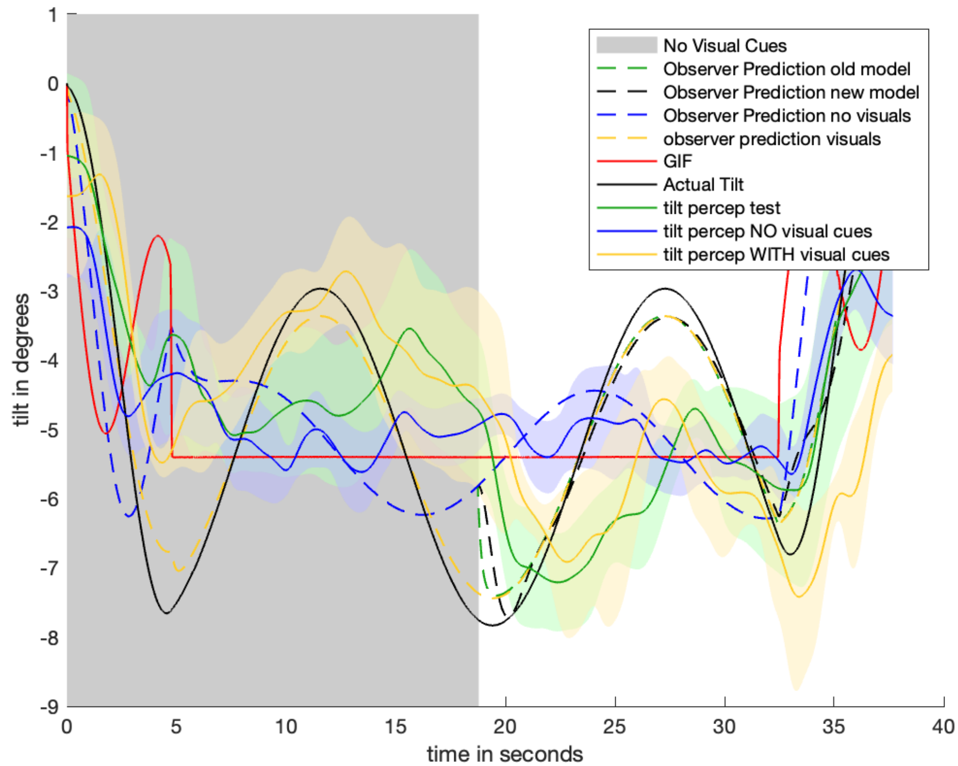
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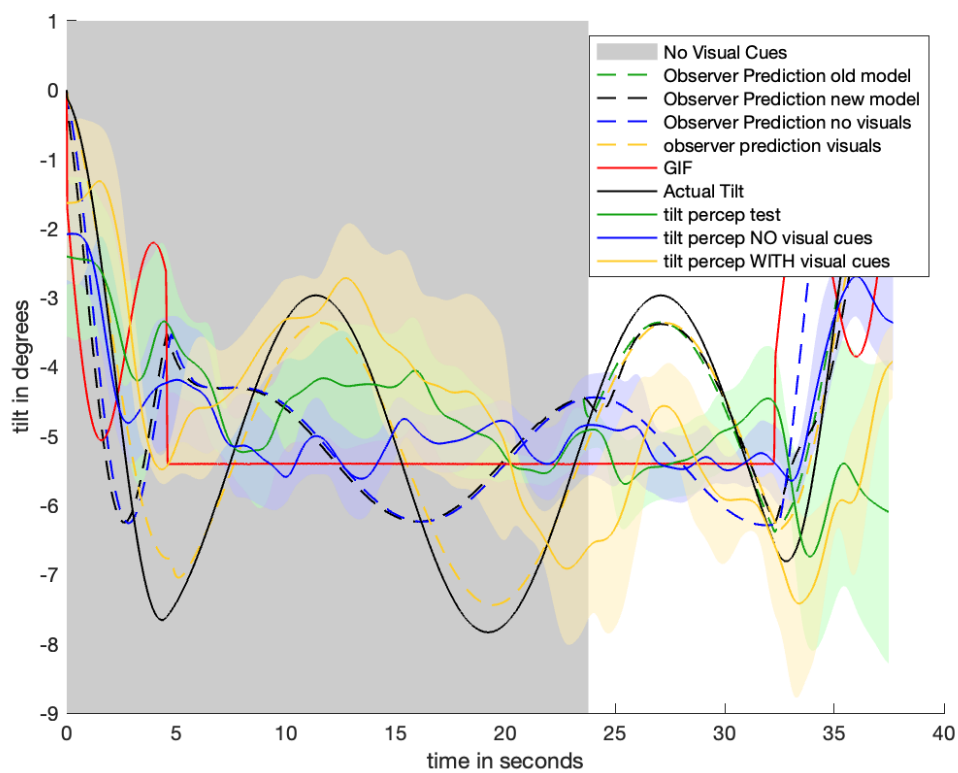
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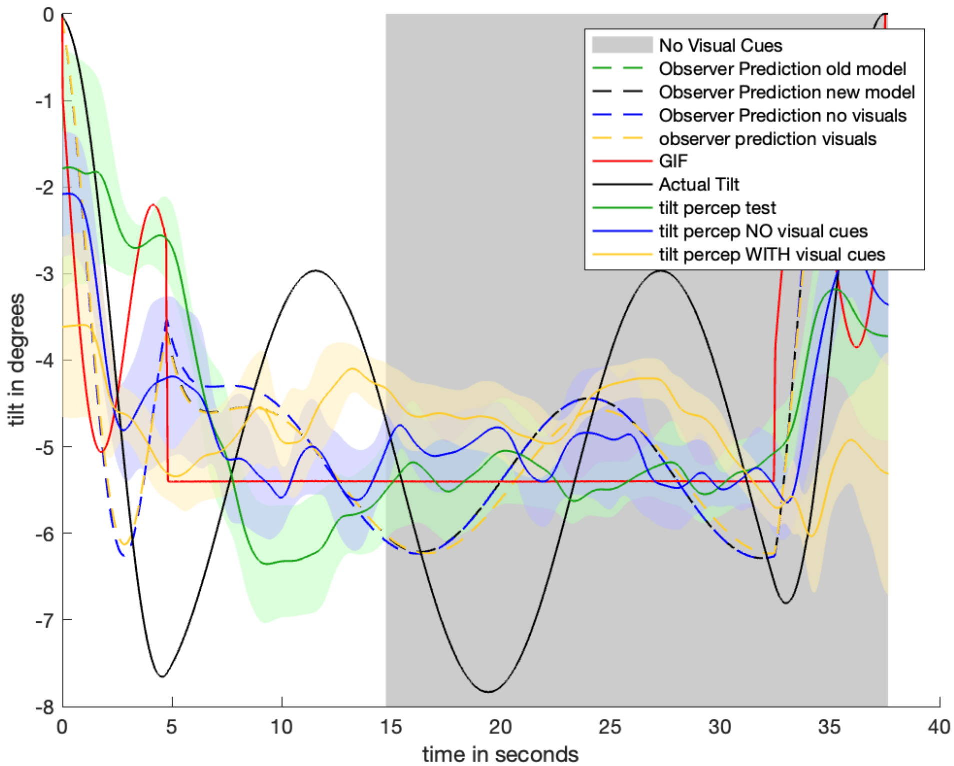
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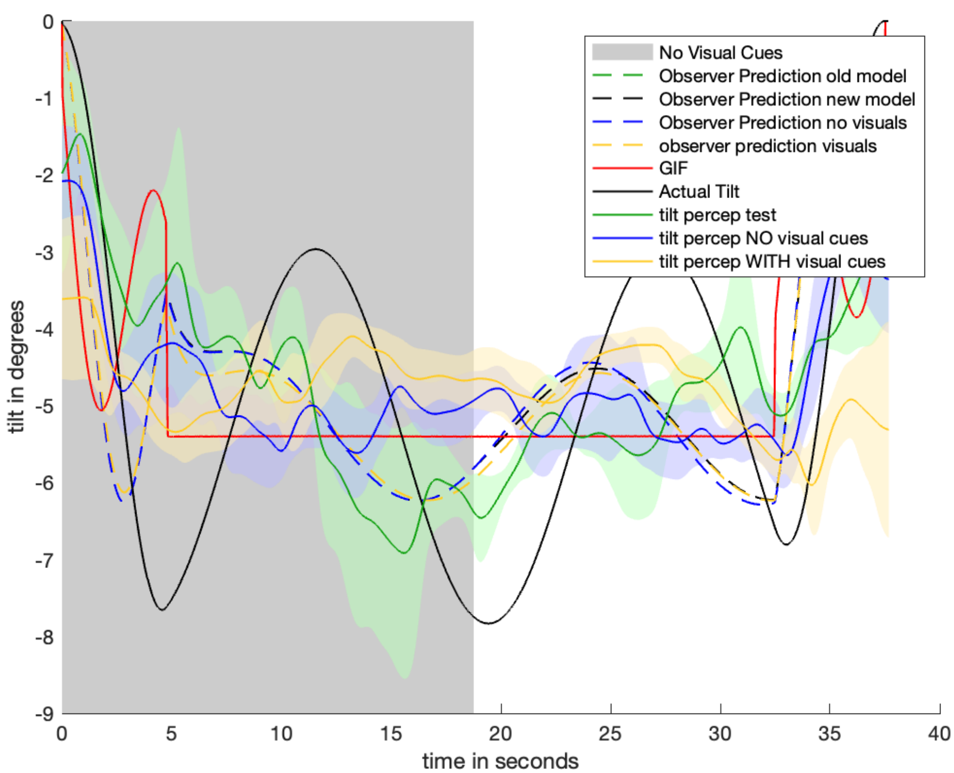
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