Gravitational Influences on Ground Dominance in Control of Egospeed

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Nathan Richard Minard

Major Professor: Steffen Werner, Ph.D.
Committee Members: Rajal Cohen, Ph.D.; Todd Thorsteinson, Ph.D.
Department Chair: Benjamin Barton, Ph.D.

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Authorization to Submit Thesis

This thesis of Nathan Minard, submitted for the degree of Master of Science with a Major in Psychology and titled "**Gravitational Influences on Ground Dominance in Control of Egospeed**," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the college of Graduate Studies for approval.

Major Professor: ____________________________ Date: _____________
Steffen Werner, Ph.D.

Committee Members: ____________________________ Date: _____________
Rajal Cohen, Ph.D.

____________________________ Date: _____________
Todd Thorsteinson, Ph.D.

Department
Administrator: ____________________________ Date: _____________
Benjamin Barton, Ph.D.

Abstract

Human perception of speed is heavily influenced by their distance from a ground plane. Previous studies have found that while controlling speed during simulated flight through an environment with both a ground plane and a plane of clouds above, humans naturally attend to speed information present in the ground plane only (Meyer, 2015). Potential factors leading to attentional selection of the ground plane under standard viewing conditions, known as *ground dominance*, include the direction of gravity, lower visual field bias, and the location of limbs (Dyre, Meyer, & Adamic, 2013). This experiment decoupled the direction of gravity from visual field and limb location by manipulating the posture of participants as either upright or supine. We continued to find evidence of altitude-speed cross-talk (confusing changes in altitude as changes in speed) in both the upright and supine conditions, providing evidence that gravity alone is not a determining factor on ground dominance.

Acknowledgements

I would like to thank Brian Dyre for seeing my potential and trusting me with a project of my own. I truly appreciated the short time we had together talking about science and music. Brian's influence on my development as a scientist was huge and I truly believe I would not be nearly as competent as I am today without his influence.

I would also like to thank Steffen Werner for taking over as my major professor after Brian's passing. I will never be able to adequately express how appreciative I am for his willingness to take up a project that used very different methods than his own.

Further I would like to thank Kellen Probert, Roger Lew, and Luke Terry. Without their help this project would never have gotten done.

Dedication

This thesis is dedicated to everyone who has supported me through my academic career, my fiancé Jasmine for her unwavering support and unparalleled formatting ability, and to whomever is reading this right now.

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Chapter 1: Introduction

Fifty-five percent of fatal aircraft accidents in commercial jet airplanes occur between the descent and landing phases of flight, totaling 28 accidents and 1,278 fatalities between 2009 and 2018 (Boeing, 2019, Federal Aviation Administration, 2018). Accurate perception, and therefore, control of speed and altitude during the landing phase of flight is critical for pilots. However, the interplay between speed and altitude introduces risks outside of the landing phase as well. The common method for gaining speed is to nose the aircraft down, sacrificing altitude for an increase in speed. This maneuver carries risk at low altitudes, which is common not only during landing, but also during combat maneuvers of fighter aircraft and agricultural aircraft that spray crops (crop-dusting).

Because altitude is often traded for speed, it is important that pilots accurately perceive speed. Flach, Warren, Garness, Kelly, and Stanard, (1997) found that participants misperceived changes in speed as a change in altitude. Flach et. al. explored this by introducing a speed disturbance into a simulated flight task that required participants to maintain a constant altitude. This phenomenon has continuously been seen in other research, namely Bennett (2006) and by work done by Dyre and colleagues (Adamic, 2011; Dyre, Meyer, & Adamic, 2013; Meyer, 2015; Wotring, 2008).

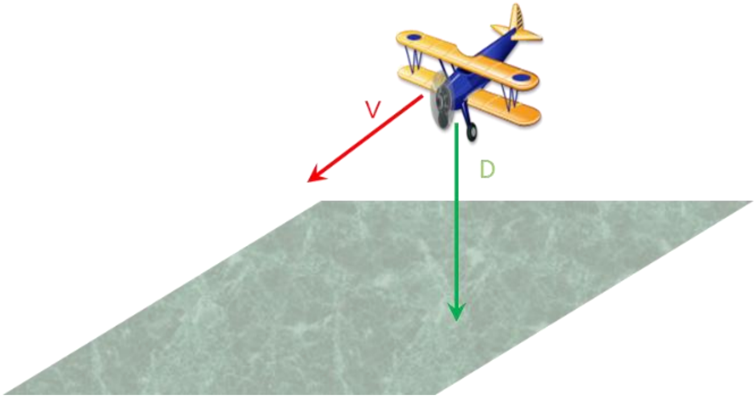

Figure 1.1: Global Optical Flow Rate in a Single Planar Environment (GOFR = V/D) (Meyer, 2015)

Gibson (1950) proposed that the human visual system bases judgements of speed and changes in altitude on optical flow. *Optical flow* is the relative velocity of texture projected to a moving point of observation as it moves through a rigid, or static, world. To describe the speed of the flow available to a dynamic observer, Warren (1982) proposed *Global Optical Flow Rate (GOFR)*, or the average flow rate available to the observer in relation to their forward speed (V) and their altitude above a planar surface (D), GOFR = V/D, (Figure 1.1). GOFR has been shown to be a dominant cue for the perception of speed (Dyre, 1997; Warren, 1982). Because GOFR is dependent on both speed and altitude for a single planar environment, it is not surprising that perceptions of speed and altitude changes can become confused.

Warren's definition expresses GOFR in units of *eye-heights per second* but is limited to the special case of a single-planar (ground only) environment. The addition of a second planar surface, such as a cloud layer above the observer, requires a revised formula because an increase in altitude will also increase the distance to the ground plane, as well as equally decreasing the distance to the cloud layer. Based on the findings of Adamic (2011), Wotring revised the definition for GOFR in a dual-planar environment defined as the amount of flow available in relation to the observer's forward speed (V) and the average distance from one plane (D_1) to the other (D_2) (Figure 1.2). With this updated formula, GOFR = $V/[(\Psi_{D_1}+\Psi_{D_2})/2]$, the altitude of the observer no longer affects the amount of flow information available.

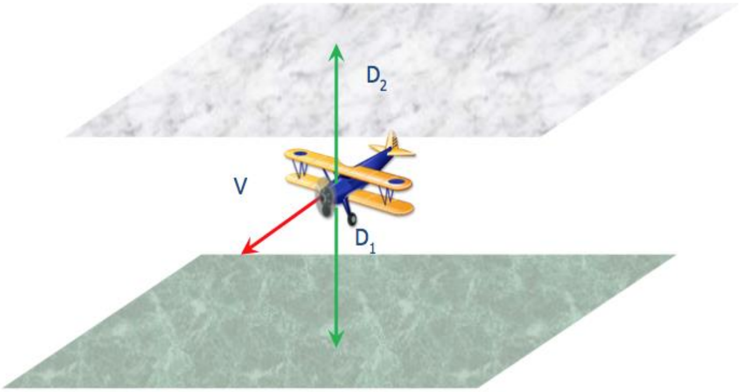

Figure 1.2: Revised Global Optical Flow Rate Formula for a Dual Planar Environment: GOFR = $V/[(\Psi_{D_1}+\Psi_{D_2})/2]$, (Meyer, 2015)

Beyond just the perception of speed, altitude changes have also been found to affect the control of speed. Bennett, Flach, McEwen, and Russell (2006) found evidence of this by giving participants control over speed in a simulated aircraft. Participants were instructed to compensate for any speed changes. Participants experienced speed (fore-aft), and altitude (vertical) disturbances. By using a spectral analysis, they were able to see that participants were making more speed control inputs when the altitude disturbance was present. More specifically, they were making more speed control inputs at the frequencies associated with the altitude disturbance. Wotring (2008) found additional evidence of this phenomenon, dubbed *altitude-speed cross-talk*, in both a single-planar environment, and a dual-planar (ground *and* sky) environment, where the participant was presented both the ground plane and a cloud layer above (Figure 1.3).

Figure 1.3: Dual Planar Environment used in Wotring (2008), Adamic (2011), and Meyer (2013)

Dyre and Wotring hypothesized that by adding a cloud layer, and thereby keeping the average rate of optical flow or *global optical flow rate* constant despite the altitude disturbances, altitude-speed cross-talk would be eliminated, due to GOFR being the predominant cue in speed perception (Dyre, 1997). However, cross-talk persisted in a dual-planar environment, which indicates that participants were processing information largely from the ground plane, which Wotring termed *ground dominance.* Meyer, Adamic, and Dyre (2013) proposed several potential explanations for the persistence of ground dominance, including color of the planes, the inability for humans to integrate flow from two surfaces, the direction of gravity, or a visual field bias. Further research by Adamic (2011) and Meyer (2015) examined factors leading to ground dominance in dual-planar environments and found that attentional shifts to the ground plane were most likely the cause but did not explore what was driving this shift. My project focuses on the potential role of the direction of gravity in driving attentional selection of the ground plane as evidenced by a difference in performance based on body orientation.

The studies by Bennett (2006), Wotring (2008), Adamic (2011), and Meyer (2013) all used similar methods to run their experiments. First, two different disturbance patterns, one for altitude, and one for speed, are constructed. These patterns were designed by combining several sine waves of different frequencies and phases into a new complex wave form that would be presented to the participants. Participant responds with a joystick to change their speed and those inputs were recorded, resulting in a complex wave form of the joystick input that can be compared to the disturbance patterns. These joystick inputs are then transformed into the frequency spectrum via a Fast Fourier Transformation (FFT), which allows the researcher to analyze which original sine waves give rise to the complex waveform. In order to adequately analyze continuous control data, this type of spectral analysis is often used. Spectral analysis allows a researcher to break down complex wave forms into their component frequencies. By defining our frequencies of interest as the frequencies used in the construction of the disturbance patterns, we are able to use spectral analysis to see if those frequencies are present in the participant's joystick inputs. We can thus determine which disturbance had a greater effect on the participants' control inputs.

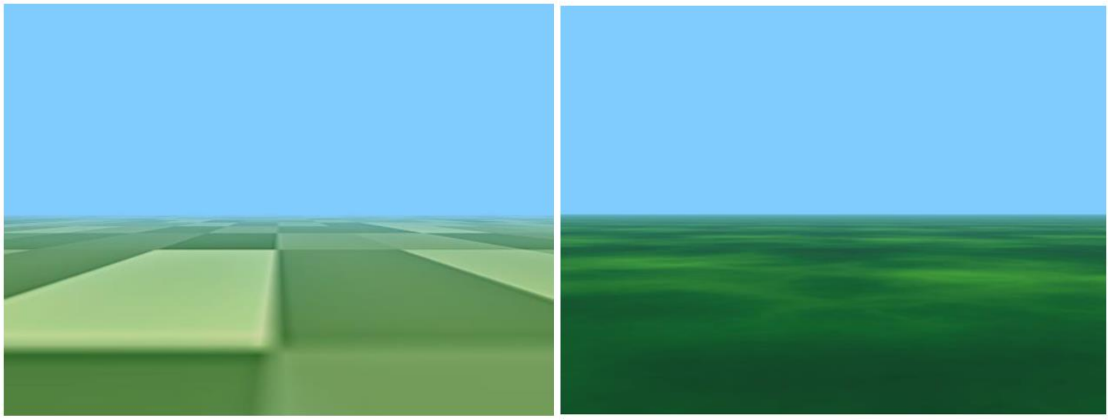

Figure 1.4: Low Spatial Frequency Plane from Bennett (2006) (left) and High Spatial Frequency Plane from Wotring (2008) The low spatial frequency bands in Bennet (2006) resulted in less flow information being available to the observer at low altitudes.

As mentioned above, Bennett et al. (2006) first explored the possibility of *altitude-speed cross-talk* and found that Root Mean Square (RMS) speed error increased when an altitude disturbance was introduced into the simulation. However, they did not find significant increases in spectral power at the altitude disturbance frequencies, so it is unclear whether the altitude disturbance produced cross-talk or simply more noise in speed control. Bennett

(2006) used a ground plane comprised of irregularly sized grids of various earth tones. The grid ground plane presented only low spatial frequencies (Figure 1.4) and therefore only little flow information while at low altitude, as optical flow is dependent on the amount of texture in an environment (Gibson, 1950).

Wotring (2008) replicated Bennett's study with modifications designed to increase power. Specifically, Wotring built planar stimuli with broadband spatial frequency, ensuring that there would still be flow information present at all altitudes.

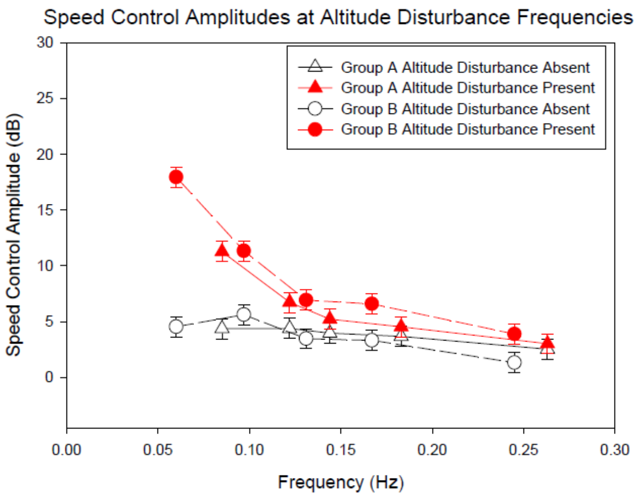

Figure 1.5: Speed Control Amplitudes at Altitude Disturbance Frequencies from Wotring (2008)

In addition to changing the ground plane, Wotring also increased the disturbance magnitudes so participants would be able to notice the acceleration changes. Disturbance magnitudes were all above the acceleration threshold, defined as a 10% increase of speed or altitude per second as per the Weber fraction (Dyre, 1997), for all frequencies, ensuring participants would be able to detect the changes in speed and altitude. Participants were instructed to maintain a constant speed while buffeted by a simulated fore-aft wind disturbance. Half of the trials also included a vertical wind disturbance. Both disturbances were built using a sum of five sine waves at interleaved frequencies with the same peak acceleration. As in Bennett (2006), participants controlled the speed of a simulated aircraft in a single-planar environment while being exposed to speed and altitude disturbances. Spectral analysis of joystick inputs at the specific disturbance frequencies showed increases in joystick manipulations at the lower altitude disturbance frequencies; an effect consistent with participants experiencing *altitude-speed cross-talk,* confusing changes in altitude with changes in speed (Figure 1.5).

The question of why cross-talk persists in a dual planar environment where the amount of flow information available according to the revised GOFR formula never changes was still unanswered. Meyer, Adamic, and Dyre (2013) hypothesized that humans were unable to use flow information presented above them. Using a condition that gave participants only the cloud layer and no ground plane, Meyer et.al. still found evidence of altitude-speed cross-talk, suggesting that humans are able to use flow from above.

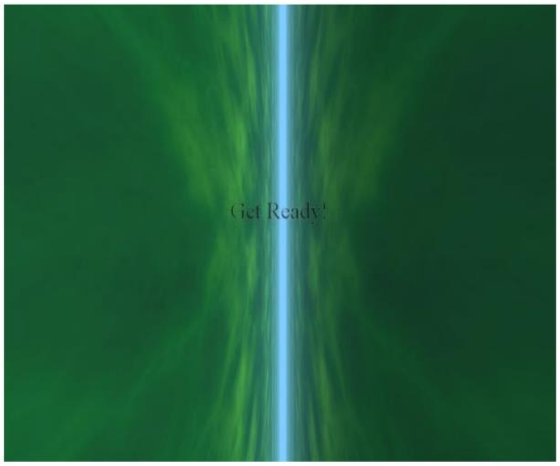

Figure 1.6: 90° shifted planes used in Dyre, Adamic, Meyer (2013)

Given that the cloud layer in isolation was able to produce cross-talk, Meyer, Adamic, and Dyre (2013) posited that ground dominance could be due to differences in luminance contrast across the planes which could affect sampling or motion integration. Lower contrast provides less information and is perceived as lower speed (Snowden, 1999). To address the contrast hypothesis, Meyer et. al. presented participants with an "inverted" environment with the blue and white swirl "sky" pattern displayed in the lower plane and the green and black swirl "ground" pattern displayed in the upper plane. Despite the lighter "sky" colored plane now appearing as the lower plane, the manipulation still showed evidence of cross-talk. Thus, cross-talk was not being driven by a terrestrial color preference. In order to explore the flow integration hypothesis, Meyer et. al. shifted the planes and disturbance patterns 90°, with the disturbance patterns moving the observer laterally instead of vertically (Figure 1.6). This forced participants to make speed control adjustments with flow information only present on the sides of the viewer. With this 90° shift, participants were now able to integrate the flow information as they were shifted laterally, resulting in an elimination of cross-talk, and therefore, changes in lateral position not being confused with changes in speed.

To examine whether *ground dominance* is the result of attentional selection, Adamic (2011) and Meyer (2015) used explicit attentional manipulations to prompt participants to sample flow information from the upper plane in a dual-planar environment. Adamic found that, in a dual-planar environment, instructions presented in the upper plane before a trial that read, “Attend the Clouds \ Ignore the Ground,” were sufficient to greatly reduce cross-talk. Using spectral analysis, Adamic (2011) and Meyer (2015) were able to observe how the joystick deflections lagged in relation to the disturbance pattern. Because the altitude disturbance pattern was defined relative to the ground plane, a positive phase lag in the joystick amplitudes when compared to the speed disturbance was consistent with a bias toward analyzing flow from the upper planar surface to control speed, and a negative phase lag suggested participants analyzed flow from the lower planar surface. In the “Attend the Clouds \ Ignore the Ground” condition, Adamic found a positive phase lag, providing evidence that the instructions did shift participants to analyze flow from the upper surface

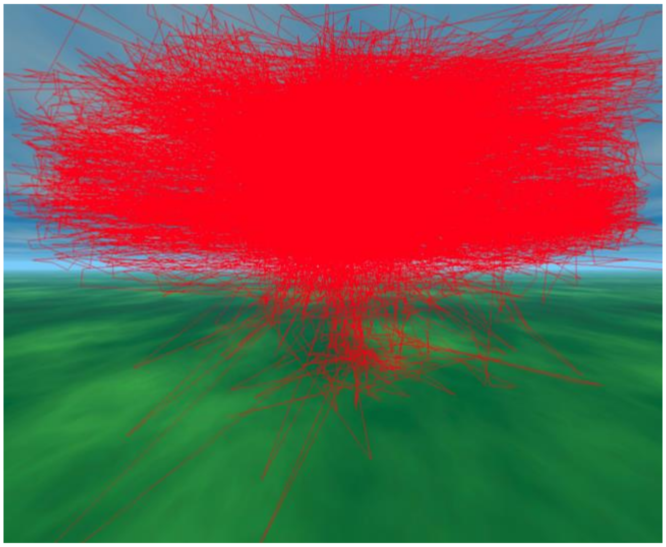

Figure 1.7: Fixation sequences for the “attend up” condition from Meyer (2015, Figure 17). Participants continued to sample information from the ground when explicitly told to attend up resulting in greater effects of cross-talk

In a follow-up study to Adamic (2011), Meyer (2015) used eye-tracking to measure attentional locus in an attentional manipulation experiment similar to Adamic. Meyer found that, in conditions where participants were instructed to attend down, attention rarely shifted to the upward plane. In the “attend up” condition, participants were more likely to engage in quick attentional shifts to the ground plane – whereas quick attentional shifts to the cloud plane were absent in the “attend down” condition (Figure 1.7). Although the total number of participants who shifted their attention downward to the ground plane was low, there was an indirect relationship between the frequency of eye fixations on the ground plane and the strength of the altitude-speed crosstalk effect. Meyer concluded that *attended* rather than *global* optical flow rate (GOFR) governed control of egospeed.

The results of these previous studies have led us to question what is causing attention to select the ground. Dyre, Meyer, and Adamic (2013) posited that direction of visual field, limb position, and gravity all might be potential underlying factors. Reed (2006) found evidence that suggests limb position can modulate attentional allocation. In an upright individual, this could draw attention to the lower plane, if the hands and feet are below the participants head. The studies of Adamic (2011) and Meyer (2015) could not differentiate these three potential factors because visual field, limb position, and gravity were all confounded with one-another. To test the specific contribution of each, the direction of gravity, visual field, and limb position need to be manipulated independently of one-another. To manipulate the direction of gravity independently of visual field, participants would need to be moved to different positions between upright and inverted. Due to these changes in body position, we will need to consider the effects that changing body position has on human physiology and vestibular information processing.

Vestibular Considerations

The ability of the human vestibular system to effectively provide balance control information without the addition of visual information is compromised while in a supine position. Vimal, Dizio, and Lackner (2017) explored balance control in situations where observers posture was upright or supine. In the upright condition participants sat upright in a chair atop an inverted pendulum that tilted about the roll axis (line of sight) and were tasked with staying upright by using a control stick. After 20 trials, participants in the upright condition were able to easily control the pendulum and stay upright; however, in the supine position, in which the chair was pitched backward 90 degrees, participants were unable to master the task of keeping themselves upright. Vimal et. al. postulated that, when the body is upright and starts to roll, the gravity-dependent otolith and somatosensory shear forces work together to inform the body of its position in space in relation to gravity. But, when the body is supine, these otolith and somatosensory forces are no longer oriented with gravity, which reduces their effectiveness in detecting changes in body position relative to the direction of gravity. These findings suggest that, when gravity is available as a cue, humans use it to maintain stabilization and it is therefore defining the location of the "ground".

Supine positions also have an effect on how humans make judgements on visual information. Harris and Mander (2014) found that body and environmental position affected perceived distance. Participants were put in a supine condition and viewed a room that was rotated so that the "floor" remained presented to a viewer's lower visual field. This resulted in participants misperceiving the length of a projected bar of light. This suggests that, human processing of depth may not be as finely tuned in a supine position as it is in an upright position.

The question remains: why do humans show an attentional preference to the ground during speed control? It may be that humans, being terrestrial creatures, are simply biased toward analyzing optical flow in the lower visual field. However, it is not yet clear what exactly is influencing these downward shifts of attention. By manipulating body posture, this thesis aims to explore this question. If a participant is in a supine position while observing the dual planar environment, the direction of gravity will be parallel to the planes. This manipulation is similar to the 90° planar shift manipulation in Dyre et. al. (2013), except that in our manipulation the participant will be rotated, resulting in the direction of gravity no longer being orthogonal to the lower visual field. Thus, if gravity is a contributing factor to ground dominance, we expect to find an elimination of cross-talk when participants are in a supine position, with a resulting phase-lag pattern of near 0 as was found in Meyer et. al. (2013). If ground dominance persists in the supine condition, we can assume that one of two phenomena are happening: either gravity is not an underlying factor in ground dominance, or it may interact with another factor, such as visual field or limb position, requiring additional position manipulations to tease these effects apart.

Chapter 2: Methods

The aim of this experiment is to test whether ground dominance in optical egospeed control is due to the alignment of the lower visual field with the direction of gravity. Using the speed maintenance task developed by Dyre and colleagues (Adamic, 2011; Meyer, 2015; Wotring, 2008), participants were tested in different postural conditions in order to disambiguate the influence of gravity from other potential factors, such as position in an observer's visual field. As in all of the studies mentioned above, participants were tasked with maintaining a constant forward speed between two textured planes, a "ground" and a "cloud" layer, while being subjected to fore-aft (speed) and vertical (altitude) wind disturbances. This experiment tested upright and supine body positions and the relation of the observer to the visual environment was held constant across body positions by rotating the display with the observer by 90 degrees in the supine position.

Design

We performed a 2 x 2 x 2 x 5 mixed factorial design experiment with a between-subjects factor of frequency assignment: "Group A", where the speed disturbance pattern is defined by a set of amplitudes and frequencies that are on average greater than the interleaving set used for the altitude disturbance, and "Group B", the inverse assignment, where the altitude disturbance frequencies are greater than the speed disturbance frequencies (see Table 2.1). We are also including three within-subjects factors of altitude disturbance (present vs absent), body position (posture) (upright vs. supine), and frequency component (1-5).

To minimize potential effects of fatigue, the experiment was performed in 2 sessions of 1.25-hour duration. Each session contained 3 blocks and each block consists of 4 trials varying in altitude disturbance and body position (posture) in a random order. Disturbance present conditions were compared to disturbance absent conditions in order to determine whether changes in altitude were misperceived as changes in speed. Participants were presented with the same visual stimuli used in Wotring (2008), Adamic (2011), and Meyer (2015) via the ViEWER simulation software package (Dyre & Grimes, 2007).

Table 2.1: Frequencies and Amplitudes used between Group A and Group B

Group A (S<A)					
Speed Disturbance					
Amplitude	183.222	70.103	38.436	23.651	10.989
Frequency	0.06	0.097	0.131	0.167	0.245
Altitude Disturbance					
Amplitude	25.418	12.338	8.856	5.484	2.655
Frequency	0.085	0.122	0.144	0.183	0.263
Group B (A<S)					
Speed Disturbance					
Amplitude	91.294	44.316	31.809	19.696	9.536
Frequency	0.085	0.122	0.144	0.183	0.263
Altitude Disturbance					
Amplitude	51.012	19.518	10.701	6.585	3.059
Frequency	0.06	0.097	0.131	0.167	0.245

Participants

Since this project is based on Wotring (2008), we performed a power analysis based on the effect sizes found in experiment 4 of that study. Based on the η_p^2 of .605 found by Wotring in for the altitude disturbance main effect, we determined that 8 participants would be the minimum number of participants required. A fully balanced design required 12 participants. Thirteen people, 8 women and 5 men were recruited to participate with an average age of 23.4 years. Eleven undergraduates from the University of Idaho Psychology Department’s subject pool were recruited via Sona Systems, and 2 graduate students from the University of Idaho Psychology department were recruited via an advertisement. One participant’s data was discarded due to failure to perform the task. Undergraduate participants received class credit for participation. Participants were informed that they would be controlling forward speed during a flight simulation while in two different body position orientations. All participants were tested for 20/30 or better Snellen visual acuity. If participants needed corrective lenses or contacts to achieve 20/30 acuity, they were asked to wear them during the experiment.

Stimuli and Apparatus

The stimuli used for this experiment were identical to those used in Wotring (2008), Adamic (2011), and Meyer (2015). Participants viewed a display simulating flight through a virtual environment. The virtual environment consisted of a textured ground and cloud layer with a width of 16,000 meters and a length of 83,000 meters (see Figure 1.3 in introduction). The textures consisted of a 256 x 256-pixel pseudo-random swirling pattern repeated 35 times, with the cloud texture composed of different shades of blue and white, and the ground layer composed of different shades of green. The edges of the texture patterns were carefully matched so it could be tiled together without creating visible seams.

The simulated environment was generated using ViEWER v2.35 (Dyre & Grimes, 2007) and presented via two Canon Data Projectors SX800 projectors with a resolution of 1400 x 1050, and a 60 Hz refresh rate (one projector was used per condition). The projectors were mounted to project an image measuring 1.3 x 1.02 meters on either a traditional vertical screen in front of the participants, or in the supine condition, a horizontal screen straight above the participant. To be consistent with the stimuli of Wotring, Adamic and Meyer, the displays were rendered as 1280 x 1024 images subtending a visual angle of 45° horizontal by 33.75° vertical (in upright position). Other than the absolute position, all relative visual parameters were identical between the upright and supine conditions. Due to technological constraints caused by the use of projectors, participants viewed the simulations in a darkened room at a distance of 1.75 meters from the display, unlike the 1.54 meters used in Wotring (2008). A “super structure” was built to isolate the supine condition from any extraneous light as well as to hold the horizontal projection screen. The superstructure consisted of two Marcy Power Cage SM-8117 exercise racks (Figure 2.1) and a rigid projection screen. The screen was mounted to ensure an identical viewing distance as the upright condition of 1.75 meters.

Figure 2.1: Supine condition (left) and upright condition (right)

Participants were presented with altitude and speed disturbances that were composed of the sums of five sine waves as defined by the two interleaved sets of frequencies (see Table 2.1). Each set of frequencies were assigned to either the speed or altitude disturbance, resulting in two groups: Group A (speed disturbance frequencies on average less than altitude disturbance frequencies), where the lower frequency set is assigned to the speed disturbance and the higher frequency set assigned to the altitude disturbance, and Group B (altitude disturbance frequencies on average greater than speed frequencies, with the opposing assignments. Frequencies and amplitudes for the disturbance frequencies were specifically chosen to ensure that when summed together into a disturbance pattern, peak acceleration for all sine waves defining the speed disturbance remained at 26.04 m/s^{-2} and peak vertical acceleration in the altitude disturbance remained at 7.25 m/s^{-2} as well as to avoid nauseogenic frequencies of 0.2-0.3 Hz (Lawtherland & Griffin, 1987). These disturbance patterns present the observer with information that is above-threshold for visually determining changes in acceleration.

Each trial of simulated flight lasted 220 seconds at an initial forward speed of 185.2 ms^{-1} and an altitude of 92.6 m, resulting in an initial GOFR of 2.0 eye-heights per second. Each trial began with a 10-second period of constant speed and altitude where the joystick was inactive. The text “Get Ready” was displayed on the screen above the horizon line. The disturbance patterns began after the “Get Ready” message disappeared, increasing from 0 to their maximum values over the course of 5 seconds. To consistently maintain their initial speed, participants manipulated a flight-simulation specific joystick (CH F-16 Combat Stick, Joystick Technologies) forward and backward with their dominant hand. The joystick is a first-order control with exponential lag with a time-constant of 100ms. The joystick recorded data at a rate of 20 Hz, with a gain of +/- 350 meters per second when deflected all the way forward or back. Movement of the joystick only affected simulated speed, not horizontal or vertical position.

A pilot study was used to test the controller settings and to make sure participants were able to safely transition between the seated and supine conditions. We found that, when the controller gain settings were set to +/- 200 meters per second, as was the case in the previous studies, 66% of the participants experienced a ceiling effect in that they had to move the joystick to its maximum position when trying to compensate for the disturbances (Figure 2.2).

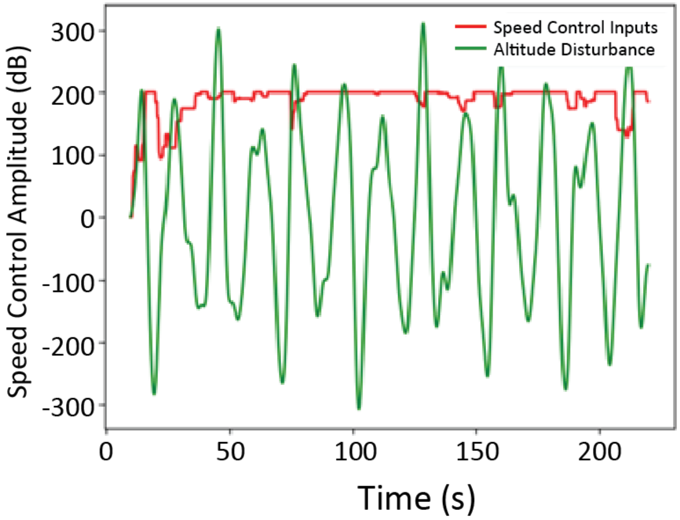

Figure 2.2: Ceiling effect of joystick amplitudes from pilot study. Participants were unable to fully overcome the disturbances and maintain goal speed

To mitigate this ceiling effect, we used a joystick gain setting of +/- 350 meters per second in the main study. This change significantly reduced the prevalence of the ceiling effect we experienced at the +/- 200 m/s gain setting which should significantly improves any spectral analysis (Figure 2.3).

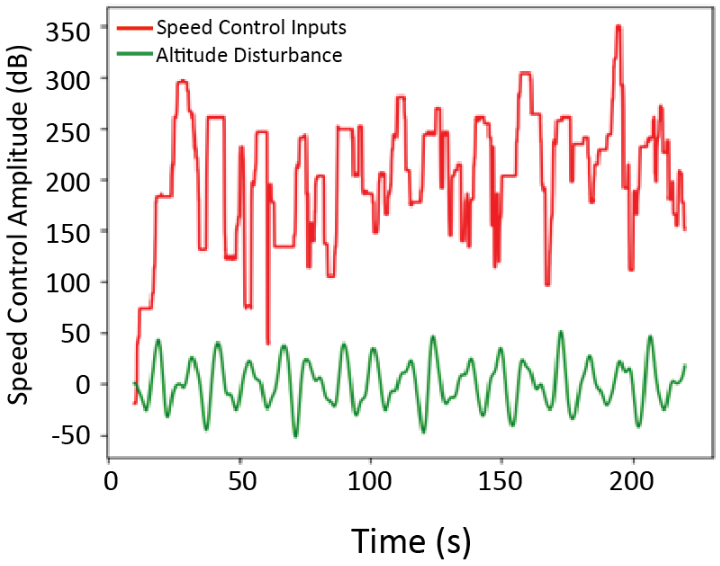

Figure 2.3: increasing the controller gain setting by +/- 150 meters per second eliminated the ceiling effect

Procedure

The procedure for our experiment was similar to Wotring (2008), with the addition of the body position manipulation. Participants were tested across 3 blocks of trials per body position for a total of 6 blocks across two 75-minute sessions on separate days. Participants were randomly assigned to a starting body position. Session one began with reading and signing of the consent form and confirming 20/30 or better visual acuity via a Snellen acuity chart. For both sessions, participants were seated or instructed to lay down in the simulator and given training on how to control speed with the joystick. The experimenter explained the participants' goal was to maintain a constant speed as defined by their initial speed during the 10 second "Get Ready" period, and as soon as the "Get Ready" message disappeared, they were free to make joystick inputs. These instructions were the same for both posture conditions.

After receiving the instructions, participants were tested in three blocks of trials for each session. Each block consisted of four unique 220 second trials, two with the altitude disturbance present, and two with the altitude disturbance absent, randomly-ordered within blocks. The speed disturbance consisted of the same sum-of-sines in each block, with phase randomly assigned. A 2-minute break was given at the end of the second block during which participants were encouraged to stand up and walk around.

Chapter 3: Results

To determine if changes in altitude were confused for changes in speed, we used spectral analysis to compare the joystick inputs when the altitude disturbance was present to the inputs when the altitude disturbance was not present at the frequencies of interest for the disturbance set. We also examined the RMS error of the joystick inputs and the phase lag patterns. This information allowed us to make better inferences about any differences between the groups. Due to a violation of the assumption of normalcy, a Box-Cox analyis was run and determined that the data necessitated a square root transformation for inferential analysis. Effect sizes are reported in-text as partial eta squared

Analysis of Joystick Amplitude at Altitude Disturbance

Table 3.1 shows the marginal means for the joystick amplitudes when compared to the frequencies of interest for the altitude disturbance. We see a higher mean joystick amplitude when the altitude disturbance is present, almost identical values based on body position (posture), higher amplitudes in Group A, and a downward trend as frequency bins increase.

Table 3.1: Marginal Means for Altitude Disturbance Data

Factor	**Level**	**Mean**	**Std. Error**	**95% Lower Bound**	**95% Upper Bound**
Altdist	Off	8.00	0.21	7.58	8.42
	On	10.39	0.26	9.87	10.91
Posture	Supine	9.27	0.25	8.78	9.76
	Upright	9.12	0.24	8.65	9.59
Group	A	9.65	0.25	9.15	10.14
	B	8.75	0.23	8.28	9.21
Frequency Bin	1	14.14	0.43	13.28	14.99
	2	11.60	0.38	10.84	12.35
	3	10.24	0.35	9.55	10.92
	4	5.72	0.19	5.33	6.09
	5	4.30	0.15	4.00	4.60

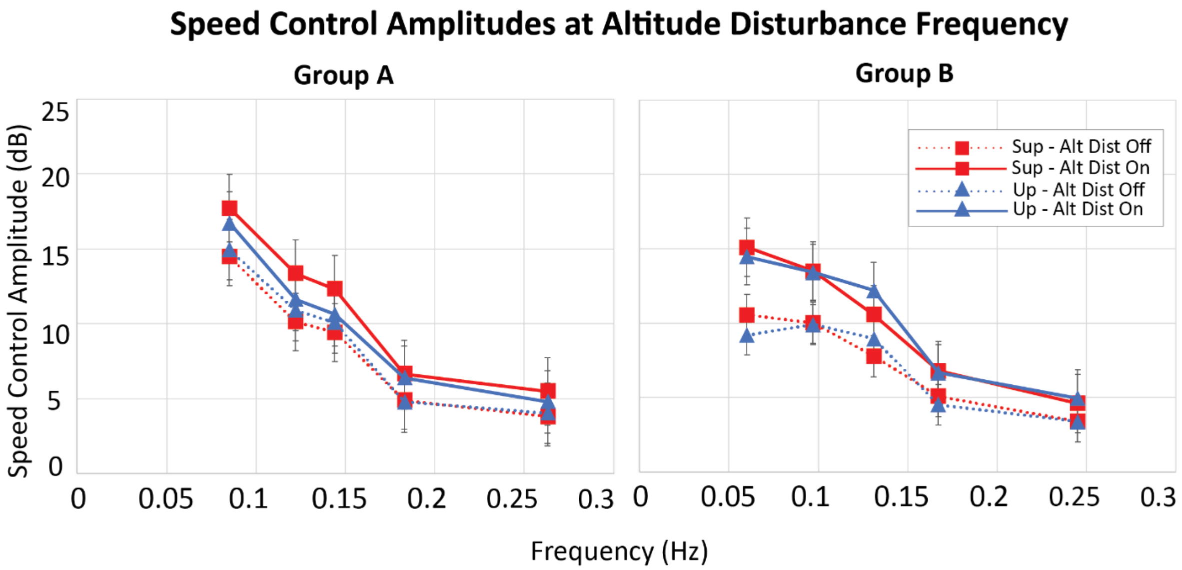

Figure 3.1: Speed control amplitudes at Altitude Disturbance Frequency Bins. We see a large separation between the on and off conditions, providing evidence of speed-altitude cross-talk

Graphing the speed control amplitudes at the altitude disturbance frequencies of interest shows evidence of altitude-speed cross-talk in both upright and supine conditions across both groups A and B (Figure 3.1), suggesting that body position is not a determining factor of altitude-speed cross-talk.

The square root transformed joystick control amplitudes were compared to the altitude disturbance frequencies in a 2x2x2x5 mixed factorial ANOVA with altitude disturbance (on vs. off), body position (posture) (upright vs. supine), group (A vs. B), and frequency component (1-5) as the four factors. We found significant main effects of altitude disturbance **$F(1,40) = 17.234$, $p = 0.002$, $\eta_p^2 = 0.63$** and frequency component, **$F(1.105,40) = 119.048$, $p < 0.001$, $\eta_p^2 = 0.91$** . No main effect was found for posture **$F(1,40) = 0.089$, $p = 0.771$** (Table 3.2). No significant interactions were found. The effect sizes for altitude disturbance and frequency component reflect a large effect.

Table 3.2: Altitude Disturbance Main Effects and Interactions central to hypothesis

Source	**Type III Sum of Squares**	**df**	**MS**	**F**	**Sig.**	**η^2_G**
Group	1.291	1, 10	1.29	0.18	0.680	0.014
altdist	7.683	1, 10	7.70	17.23	0.002	0.075
altdist * Group	0.967	1, 10	1.00	2.16	0.172	0.010
posture	0.047	1, 10	0.00	0.08	0.771	0.001
posture * Group	0.320	1, 10	0.30	0.60	0.456	0.003
Freqbin	89.88	1.08, 0.254	83.00	119.04	0.000	0.488
Freqbin * Group	1.839	1.08, 0.254	1.70	2.43	0.147	0.019
altdist * posture	0.301	1, 10	0.30	1.39	0.265	0.003
altdist * posture * Group	0.445	1, 10	0.40	2.06	0.182	0.005
altdist * Freqbin	0.193	2.43, 0.733	0.10	2.29	0.113	0.002
altdist * Freqbin * Group	0.253	2.43, 0.733	0.10	3.02	0.059	0.003
posture * Freqbin	0.229	2.48, 0.476	0.10	1.61	0.215	0.002
posture * Freqbin * Group	0.284	2.48, 0.476	0.10	2.00	0.148	0.003
altdist * posture * Freqbin	0.069	2.73, 0.684	0.00	0.74	0.526	0.001
altdist * posture * Freqbin * Group	0.036	2.73, 0.684	0.00	0.38	0.745	0.000

**df presented as source, error. All df with non-whole values are the result of Greenhouse-Geisser correction for sphericity*

Analysis of Joystick Amplitude at Speed Disturbance

Table 3.3 shows the marginal means for the joystick amplitudes when compared to the frequencies of interest for the speed disturbance. We see a higher mean joystick amplitude when the altitude disturbance is present, almost identical values based on posture, higher amplitudes in Group A, and a downward trend as frequency bins increase. This is the same pattern we found in the analysis of joystick amplitudes at altitude disturbance frequencies.

Table 3.3: Marginal Means for Speed Disturbance Data

Factor	**Level**	**Mean**	**Std. Error**	**95% Lower Bound**	**95% Upper Bound**
Altdist	Off	9.72	0.30	9.13	10.31
	On	11.74	0.32	11.09	12.38
Posture	Supine	10.68	0.31	10.07	11.30
	Upright	10.77	0.32	10.14	11.40
Group	A	13.29	0.36	12.58	14.01
	B	8.16	0.21	7.73	8.59
Frequency Bin	1	18.81	0.68	17.46	20.16
	2	12.40	0.43	11.55	13.24
	3	9.54	0.32	8.90	10.18
	4	7.54	0.26	7.02	8.07
	5	5.34	0.19	4.96	5.72

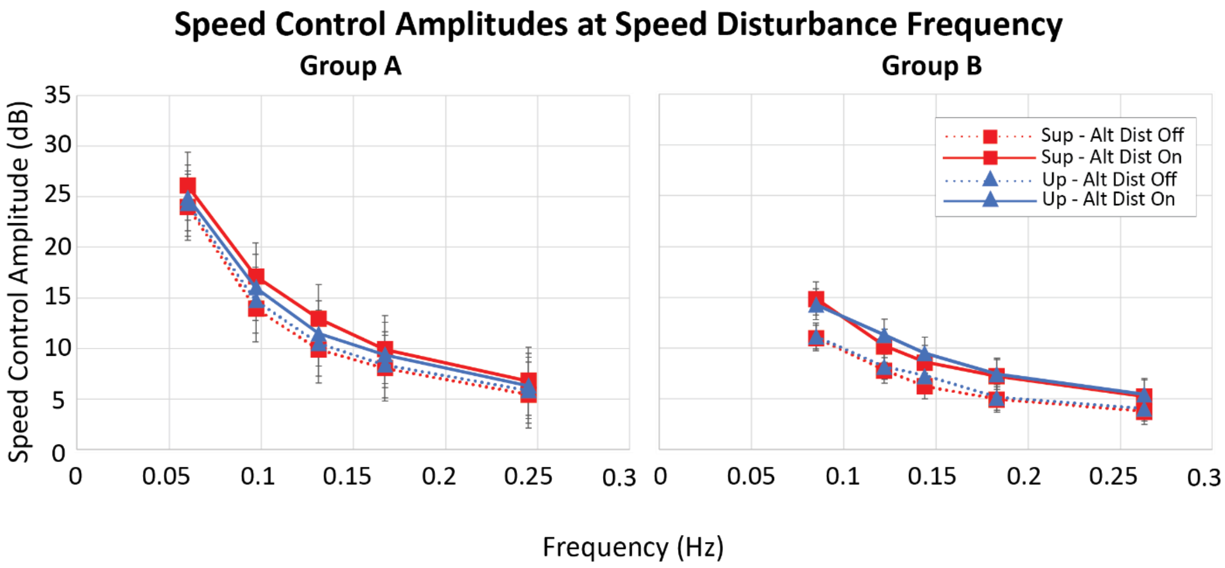

Figure 3.2: Speed control amplitudes at Speed Disturbance Frequency Bins. We see a large separation between the on and off conditions in group B, and a less marked, but still present separation in group A, providing evidence of speed-altitude cross-talk

Graphing the speed control amplitudes at the altitude disturbance frequencies of interest shows evidence of altitude-speed cross-talk in both upright and supine conditions across both groups A and B (Figure 3.2), although somewhat muted in the upright condition of group A. This suggests, like in the analysis of joystick amplitude at the altitude disturbance, that body position is not a determining factor of altitude-speed cross-talk.

The square root transformed joystick control amplitudes were compared to the speed disturbance frequencies in a 2x2x2x5 mixed factorial ANOVA with altitude disturbance (on vs. off), posture (upright vs. supine), group (A vs. B), and frequency component (1-5) as the four factors. We found significant main effects of altitude disturbance **$F(1,40) = 12.125$, $p = 0.006$, $\eta_p^2 = 0.54$** and frequency component, **$F(1.105, 40) = 185.942$, $p < 0.001$, $\eta_p^2 = 0.94$.** No main effect was found for posture **$F(1,40) = 0.003$, $p = 0.958$** (Table 3.2). We found a significant two-way interaction of frequency component and group, **$F(1.014,40) = 14.472$, $p = 0.003$, $\eta_p^2 = 0.49$** (Table 3.4). No other main effects or interactions were significant (Table 3.4).

Table 3.4: Speed Disturbance Main Effects and Interactions central to hypothesis

Source	**Type III Sum of Squares**	**df**	**MS**	**F**	**Sig.**	**η^2_G**
Group	31.68	1, 10	31.68	3.44	0.093	0.216
altdist	5.33	1, 10	5.33	12.12	0.006	0.044
altdist * Group	1.04	1, 10	1.04	2.36	0.155	0.009
posture	0.002	1, 10	0.00	0.00	0.958	0.000
posture * Group	0.66	1, 10	0.66	0.83	0.383	0.006
Freqbin	103.20	1.01, 0.254	101.80	185.94	0.000	0.472
Freqbin * Group	8.03	1.01, 0.254	7.92	14.47	0.003	0.065
altdist * posture	0.53	1, 10	0.53	1.76	0.214	0.005
altdist * posture * Group	0.26	1, 10	0.26	0.88	0.369	0.002
altdist * Freqbin	0.08	2.93, 0.733	0.03	2.09	0.124	0.001
altdist * Freqbin * Group	0.10	2.93, 0.733	0.03	2.41	0.087	0.001
posture * Freqbin	0.12	1.9, 0.476	0.06	1.12	0.343	0.001
posture * Freqbin * Group	0.06	1.9, 0.476	0.03	0.54	0.578	0.001
altdist * posture * Freqbin	0.02	2.74, 0.684	0.00	0.29	0.809	0.000
altdist * posture * Freqbin * Group	0.02	2.74, 0.864	0.00	0.31	0.797	0.000

**df presented as source, error. All df with non-whole values are the result of Greenhouse-Geisser correction for sphericity*

Analysis of RMS Error of Joystick Amplitudes

Table 3.5 shows the marginal means of the Root Mean Square (RMS) error of joystick amplitudes. We found a slightly higher amount of error when the altitude disturbance was off, slightly more error in the upright condition, and higher error in Group A than in Group B.

Table 3.5: Marginal Means for RMS Error of Joystick Amplitude

Factor	**Level**	**Mean**	**Std. Error**	**95% Lower Bound**	**95% Upper Bound**
Alt Dist	Off	231.99	4.64	222.89	241.09
	On	222.63	4.81	213.19	232.08
Posture	Supine	223.92	4.63	214.83	233.00
	Upright	230.71	4.83	221.22	240.19
Group	A	250.21	21.35	241.93	258.50
	B	204.41	21.35	195.67	213.14

The RMS error of the joystick control amplitudes were compared in a 2x2x2 mixed factorial ANOVA with altitude disturbance (on vs. off), posture (upright vs. supine), and group (A vs. B) as the three factors. We found no significant main effects or interactions (Table 3.6). This finding shows that across the main factors of interest, the overall rates of error were not significantly different.

Table 3.6: Effects of RMS Error

Source	**Type III Sum of Squares**	**df**	**MS**	**F**	**Sig.**	**η^2_G**
Group	80502.00	1, 10	36.98	4.55	0.059	0.26
altdist	1049.20	1, 10	1049.20	1.03	0.333	0.01
altdist * Group	1386.10	1, 10	1386.10	1.36	0.270	0.01
posture	553.20	1, 10	553.20	1.42	0.261	0.00
posture * Group	6.88	1, 10	6.88	0.01	0.897	0.00
altdist * posture	0.45	1, 10	0.45	0.00	0.958	0.00
altdist * posture * Group	0.90	1, 10	0.90	0.00	0.941	0.00

Analysis of Phase Lag

Analysis of the phase lag present in the joystick amplitudes offers information regarding which plane participants sampled speed information. By examining the extent at which the joystick amplitudes lag in relation to the altitude disturbance, we can gain insight into which plane is being attended to. If the phase lags are negative in relation to the altitude disturbance then we can be confident that participants are primarily using the ground plane for speed perception and control.

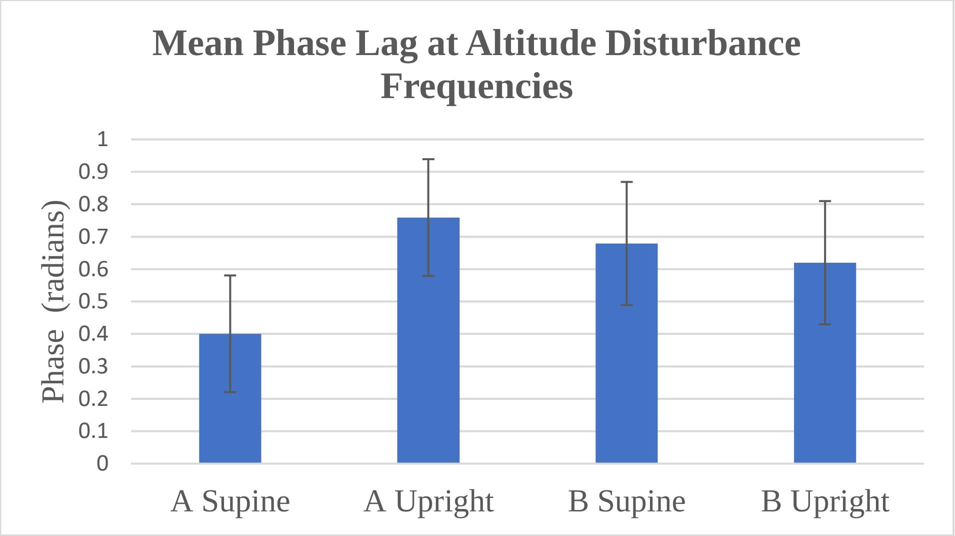

Figure 3.3: Mean phase lag values for each group and condition. This graph notes how out of phase the joystick amplitudes are when compared to the altitude disturbance frequencies. Error bars represent averaged standard error of paired comparisons.

No significant main effects or interactions were found for the phase lag of joystick inputs at the altitude disturbance frequencies (Table 3.7). We found no significant differences in the phase lag patterns across groups and posture conditions.

Table 3.7: Effects of Phase Lag at Altitude Disturbance Frequencies

Source	**Type III Sum of Squares**	**df**	**MS**	**F**	**Sig.**	**η^2_G**
Group	0.029	1, 10	0.029	0.139	0.717	0.009
posture	0.135	1, 10	0.135	1.252	0.289	0.041
posture * Group	0.262	1, 10	0.262	2.435	0.150	0.076

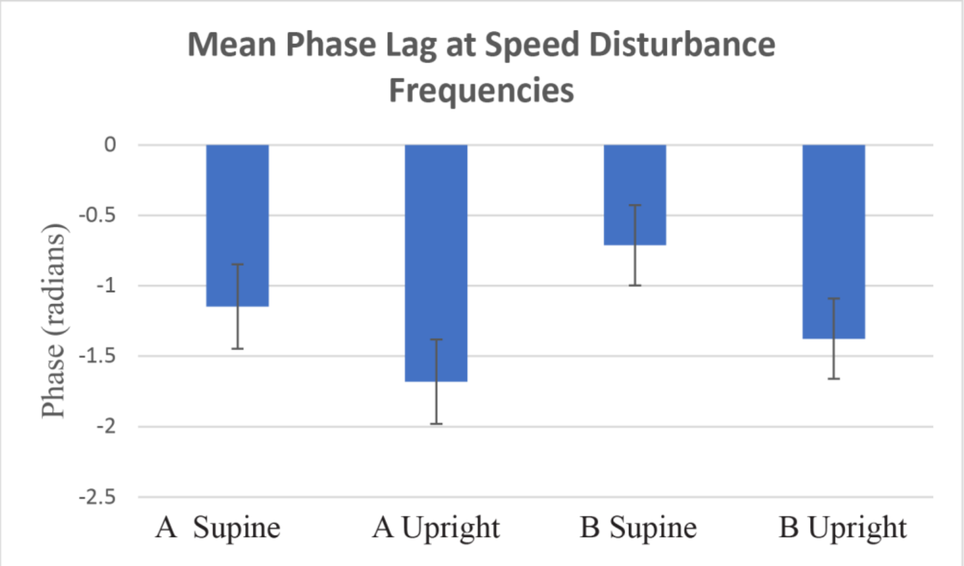

Figure 3.4: Mean phase lag values for each group and condition. This graph notes how out of phase the joystick amplitudes are when compared to the speed disturbance frequencies. Error bars represent averaged standard error of paired comparisons.

We found a significant effect of posture on the phase lag at the speed disturbance frequencies, **F(1, 10) = 4.739, p = 0.04,** with the phase lag being smaller in the supine conditions.

Table 3.8: Effects of Phase Lag at Speed Disturbance Frequencies

Source	**Type III Sum of Squares**	**df**	**MS**	**F**	**Sig.**	**η^2_G**
Group	0.819	1, 10	0.819	1.563	0.225	0.068
posture	2.485	1, 10	2.485	4.739	0.041	0.160
posture * Group	10.488	1, 10	0.483	0.922	0.348	0.002

Chapter 4: Discussion

Discussion of Results

Our hypothesis that the direction of gravity is a contributing factor to ground dominance, was not supported. We failed to find a significant effect of body position on speed control inputs at the altitude disturbance frequencies, nor did we find any interaction of posture with any of the other variables. While this result rules out a simple effect of gravity, it does not preclude the potential of a more complex interaction between gravity and visual field bias or effector location as contributing factors to ground dominance. A future experiment would need to include manipulations to disambiguate these additional factors. Dyre et. al. (2013) suggested that an inverted position would be able to examine the effect of visual field bias by fully inverting a participant. If they continued to show a preference to a lower (ground) plane while inverted, it would suggest a visual field bias as a contributing factor.

The continued evidence of speed-altitude crosstalk is in line with the findings of Wotring (2008), Adamic (2011) and, Meyer (2013). We also continue to see the trend of lower frequency disturbances resulting in higher power in the joystick amplitudes, and higher frequency disturbances resulting in lower power in the joystick amplitudes. This was a welcome finding due to the numerous changes that had to be made to the experiment for it to work within the parameters we had. This was the first experiment in the series that did not use a 1.3 m NEC (MultiSync XG-1350) rear-projection display, instead using a projector, which limited our ability to reproduce the exact same display size.

Our study required changing the differential gain settings of the joystick by +/- 150 m/s, giving us a final gain setting of +/- 350 m/s. During pilot testing it was discovered that at regular cycles in the A group, a full joystick deflection forward would result in the simulated aircraft not moving. The gain of the joystick was not large enough to overcome the effect of the disturbance. It is unclear how previous studies (Adamic, 2011; Dyre et. al., 2013; Meyer, 2015; and Wotring, 2008), were able to overcome this issue.

Although our main hypothesis was not supported, we found that that both the altitude on and off conditions showed a similar downward trend in joystick amplitudes as the frequencies got higher (see Figures 3.1 and 3.2). This trend was not present in the results of Wotring (2008), with the altitude off conditions showing a mostly flat trend across frequencies, suggesting that in Wotring's study, there was very little effect of the speed disturbance on the joystick inputs. In order to investigate this phenomenon, we looked at unpublished data from a previous experiment and found a similar trend to that found in this study. Further, the data patterns shown in Figures 3.1 and 3.2 did not fully match those found in Wotring (2008) (see Figure 1.5, this paper's introduction). Wotring's study, having been one of the earliest in this line of research, could be suffering from some sort of effect that is not present in subsequent studies. A future study could benefit from reanalyzing the data from Wotring (2008), Adamic (2011), and Meyer (2013), to determine what is causing this pattern to disappear.

The phase lag findings in this study were unclear as we found the opposite of what we expected, specifically, we found positive phase lag when the joystick amplitudes were compared to the altitude disturbance frequencies. The findings by Adamic (2011), Meyer (2015), and Wotring (2008) all showed evidence of ground dominance via a negative phase lag when compared to the altitude disturbance frequencies. Despite this difference, the direction of phase lag is consistent for the supine/upright conditions and there does not seem to be a qualitative shift in phase despite a weak effect on body position. Our findings are unclear as the direction of the lag is consistent for the upright/supine. The discrepancy of our findings to the established results could be due to a simple sign change done post-hoc in the previous studies. We examined this potentiality by defining a simple sine wave and attempted to stay out of phase with the disturbance. We found that as the value for the altitude disturbance decreased, the simulated aircraft would be pushed upwards away from the ground plane, suggesting that being positively out of phase with the disturbance would suggest that the participant was using the ground plane for speed information.

Potential Implications

Based on the findings in this study, it seems that humans prefer to sample information for speed control from information in their lower visual field in conditions where gravity is uninformative. This has implications in several different applied settings, such as spaceflight where "down" is relative to each individual, or during the development of augmented reality head-up display (HUD) for speed information based on optical flow. Despite this experiment using a simulated flight task, these findings also have implications for terrestrial vehicles.

When designing HUD's for use in vehicles, positioning important information, such as a speedometer, or the fuel gauge, in the lower visual field would take advantage of the natural tendency to sample information more frequently towards the ground. Further, designers of augmented reality technologies could use the principals of GOFR to produce additional flow fields to be used in low-vision conditions, such as during heavy fog or white out conditions to reintroduce flow information to the driver. This application would require further studies to determine how much flow information is used when also presented with a numerical indicator of speed.

Overall, the direction of gravity does not seem to have an effect on our ability to process speed information, and use that information to make control inputs. This opens up the possibility of using a supine position in tasks that require speed control without a significant reduction in performance. Similar to how some military aircraft, such as the Boeing KC-135 refueling aircraft, require a belly down supine position due to a cramped workspace, a military application of a belly-up supine position for some kind of speed-control piloting task without concurrent task such as a navigation task, could potentially be used in the future.

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