SLOPE, DISTANCE, AND HEIGHT ESTIMATION OF LUNAR AND LUNAR-LIKE TERRAIN IN A VIRTUAL REALITY ENVIRONMENT

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ABSTRACT

Introduction: Future lunar excursions will require accurate navigational assistance. Current and future technology will likely be available; however, the human's own perception of the terrain may affect their confidence in these instruments and be necessary during emergency situations. This study examines the inherent errors of terrain estimation humans make within lunar-like and lunar Virtual Reality environments. **Methods:** The effects of true slope, distance, sun elevation, and body position on slope, distance, and height estimates of synoptically viewed images of lunar-like terrain (20 subjects) and synoptically viewed Apollo panoramic images (25 subjects) were determined using mixed regressions and paired t-tests. Systematic and random errors were determined for all estimates. Slope estimate comparisons were made between lunar hills and craters. **Results:** Slope was significantly overestimated ($p < 0.05$) with large between-subject errors. Slope estimates were significantly greater at lower sun elevations and closer distances in the VR Study. Both slope and distance estimates were significantly greater from a lunar G_z supine position. Lunar distance estimates varied largely and slope estimation errors were significantly greater for craters than for hills. **Conclusions:** The development of a VR training tool to calibrate an astronaut's slope, distance, and height perception prior to lunar missions and the integration of terrain perception with navigational devices would enhance safety and efficiency of future lunar missions.

KEYWORDS

aerial perspective, non-Lambertian reflectance, slope, distance, height, sun elevation, body position

The unique lunar environment presents unfamiliar conditions that caused difficulties for the Apollo astronauts and poses risks to the safety and efficiency of future lunar excursions. Without an atmosphere, the lack of aerial perspective (haze) eliminates a common cue that makes distant objects appear fainter and farther away (**Figure 1,** Jones & Glover, 2008). Apollo 14 Astronaut Al Shepard remarked: "It's crystal clear up there – there's no closeness that you try to associate with it in Earth terms – it just looks a lot closer than it is" (10). The lack of an atmosphere also prevents the scattering of light, allowing the formation of deep shadows (**Figure 2**, Jones & Glover, 2008)), especially at low sun elevations that distorted Apollo 12 Astronaut Al Bean's slope perception, causing him to overestimate the 11 degree side of the Surveyor Crater by almost 30 degrees when partially concealed by a shadow (Heiken & Jones, 2007). The non-Lambertian reflectance properties of the lunar regolith preferentially reflect light directly back to its source, known as backscatter (**Figure 3,** Jones & Glover, 2008). Backscatter causes a spike of brightness intensity when viewing terrain directly away from the sun's azimuth, washing out surface texture and causing Apollo 16 Astronaut John Young to temporarily lose visibility of the craters lying before him (Heiken & Jones, 2008). The lack of familiar, recognizable objects on the lunar surface inhibits one's ability to use the relationship between size and distance of an object to scale one's reference frame correctly (**Figure 4,** Jones & Glover, 2008). Apollo 12 Astronaut Pete Conrad mistakenly judged a 500 m diameter crater that was 4500 m from his position as only 35 m in diameter and 300 m away (Heiken & Jones, 2007). These misperceptions could cause astronauts to become spatially disorientated (i.e. lost) and make flawed and potentially life-threatening decisions. Finally, the reduced gravity of the lunar environment may also distort visual perception by inhibiting one's ability to judge the down vector, the depth of objects, or even the use of size-constancy (Clement, Lathan & Lockerd, 2008). These challenges necessitate an understanding of visual perception in the lunar environment, methods with which to make accurate judgments, and development of training protocols and instruments that will help overcome future navigational difficulties.

Figure 1. *Lack of Aerial Perspective to discriminate the distance to the Mons Vitruvius (left) and the South Massif (right) in the Taurus-Littrow Valley from Apollo 17.*

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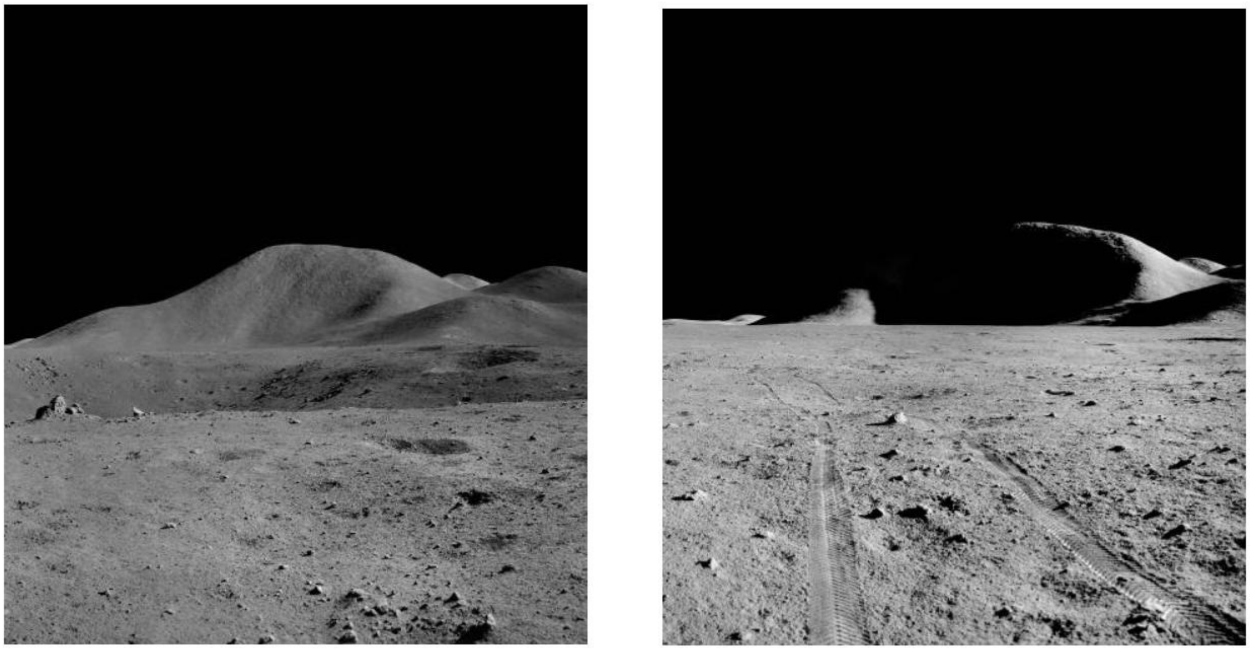

Figure 2. *Formation of deep shadows concealing terrain on the lunar surface.*

Figure 3. *Changes in brightness and contrast of the lunar surface when viewing "up-sun" (left), "down-sun" (center), and "cross-sun" (right).*

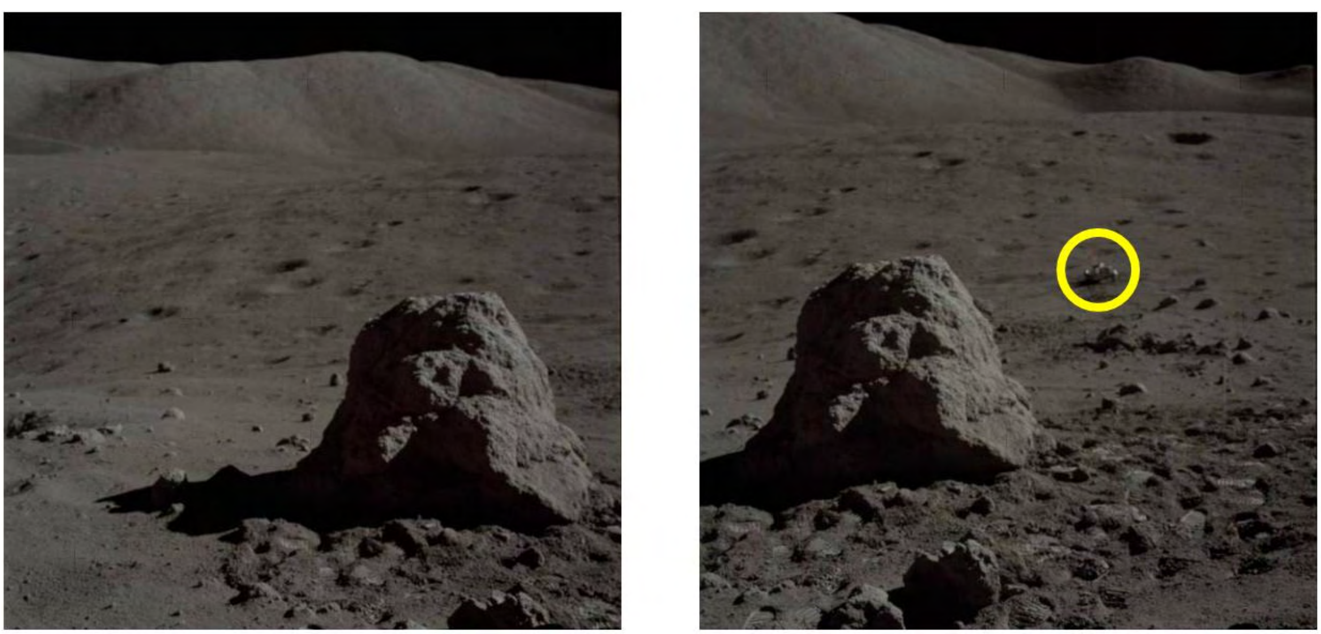

Figure 4. *The absence of familiar objects on the lunar surface hinders the determination of distance (left). The size of the lunar rover provides clues to the vast distance (right).*

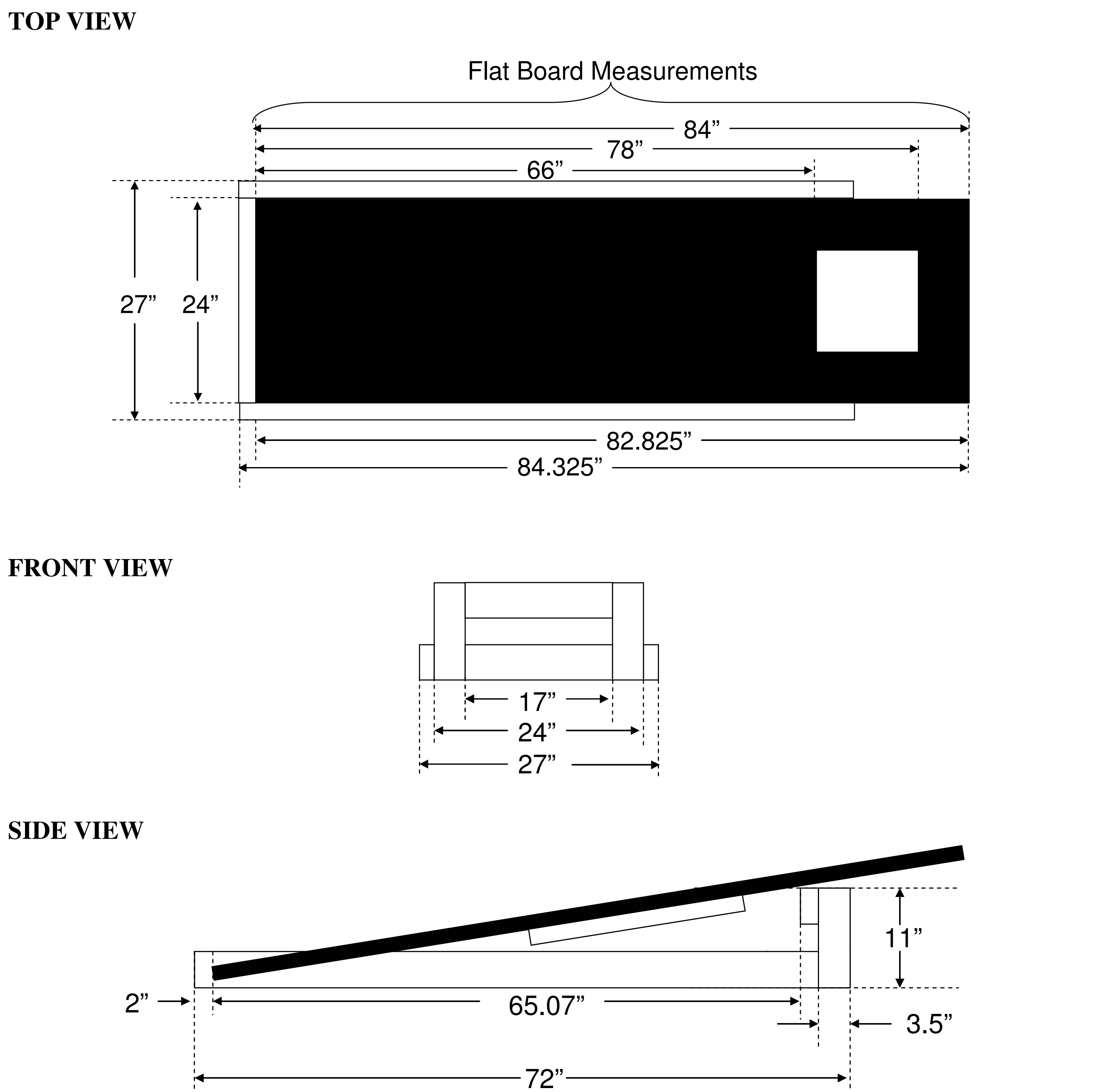

Figure 5. *Dimensions of the supine support structure*

NASA’s Vision for Space Exploration calls for a return to the Moon for extended time periods, allowing astronauts to search for resources and teaching them how to safely work in a harsh environment (NASA, 2008). Astronauts will make repeated excursions, with and without the use of a rover, and will be subject to uncertainties of the lunar surface and map limitations (Young, 2007). Planning and implementation of pre-defined routes with the aid of LIDAR/RADAR data, topographical maps, and laser ranging devices will likely be available, as well as path optimizing devices that considers locomotion risks and metabolic costs (Young, 2007). In addition to these sources of information, astronauts will use their own perception of terrain when making navigational decisions. However, just as aircraft pilots experience conflicts between their perceptual inputs and the aircraft instruments, astronauts may also experience conflicts between the appearance of slopes and distances on the lunar surface and the information provided by their navigational instruments. These conflicts may not only reduce their trust in these instruments, but may result in erroneous and even life-threatening decisions during emergencies without the availability of these instruments. This study identifies the magnitude and variability of the perceptual errors humans make while judging lunar-like and lunar terrain and provides justification for investigating solutions to overcome these potentially dangerous conditions.

METHODS

Study Design

Two experiments were conducted at the MIT Man Vehicle Laboratory to measure and compare slope, distance, and height estimates of lunar and lunar-like terrain in a Virtual Reality (VR) environment. The Lunar-like VR Study (MVS) used photographs taken from the area around the Mars Society Mars Desert Research Station (MDRS), consisting of three hills with different slopes (14.3^o, 19.2^o, and 22.8^o) at two distance (25 m and 75 m), and two sun elevations (10^o and 33^o). Subjects viewed the images in a pseudo-random order and reported slope and distance (to the base of the hills) estimates while either standing (Earth G_z;) or 10^o above supine (Lunar G_z). Subjects in the Lunar VR Study (LVS) viewed Apollo mission images acquired from Arizona State University and the *Apollo Lunar Surface Journals*. Six hills (14.7^o – 25.6^o) at two distances each (in the range 4000 m – 13900 m) were presented in a pseudo-random order. Subjects again made slope, distance to the hill base, and height estimates were collected. Images of six craters (7^o – 30^o) were also presented in a pseudo-random order and estimates of slope and distance across the crater estimates were collected in the same body positions. Both experiments were approved by the MIT Committee on the Use of Humans as Experimental Subjects.

Subjects

Twenty-five subjects were recruited for the MVS but five subjects were excluded from the results analysis due to prior knowledge of the experiment and failure to follow the instructions of the experiment. Of the 20 remaining subjects used within the analysis, gender was disproportional (16 males, 4 females) and excluded from the analysis and age ranged from 20 – 40 years. All subjects possessed normal or corrected-to-normal vision with the exception of one subject whose corrected vision was 20/50. One subject possessed prior scientific knowledge of slope estimation studies, as well as extensive VR experience. This subject was included without any evidence or indication that his naivety of the stimuli was compromised by prior knowledge. Thirty-one subjects were recruited for the LVS and six subjects were excluded from the analysis for the following reasons: completing a pilot study version of the experiment (2), not completing the experiment (2), and failure to follow the instructions (2). Of the 25 subjects whose data were analyzed, 11 had previously participated in the MVS. Gender was disproportional (20 males, 5 females) and was not analyzed as a factor affecting estimates. Age ranged from 20 – 40 years and all subjects possessed normal or corrected-to-normal vision.

Test Equipment

The actual slope and distance of the hills in the MVS were measured on-site using a *Bushnell Pinseeker 1500 w/Slope* Laser Rangefinder (LRF), which has a reported accuracy of ± 1 meter and a slope range between 0 and 20 degrees with an accuracy of ± 1 degree. The instrument's slope output is the angle between the horizontal and the straight line distance between the LRF and the target object. The actual slope of each hill was calculated using the output of the LRF and the Law of Sines/Cosines. *Sony V3* digital cameras were used to collect images of each hill within the MVS. The images were displayed using an nVis nVisor SX binocular Head-Mounted Display (HMD) with a 1280 x 1024 pixel resolution and a 60^o diagonal FOV. To preserve the vertical FOV of the photographs, the images were scaled and cropped horizontally to fit within the HMD display. A supine support structure allowed subjects to wear the HMD while positioning their body so 1/6th G acted along their longitudinal body axis. The dimensions of this structure are shown in **Figure 5.**

Experimental Protocol

All subjects first completed the Subject Consent Form and Subject Information Form. Within the MVS, all 12 possible combinations of slope, distance, and sun elevation conditions were viewed in each of 4 sessions in a random order, without presenting any one hill consecutively. Sessions 3 and 4 were a repetition of sessions 1 and 2. Sessions 1 and 4 were conducted in the standing position, and sessions 2 and 3 were conducted in the supine support structure. A training session, containing five images of other lunar-like hills preceded the four main sessions and allowed subjects to practice using the estimation devices. A red box appeared over the region of the hill to be estimated and remained visible for 3 seconds. At any point during the experiment, subjects could re-highlight the region to be estimated by pressing the left mouse button. The slope estimation device consisted of adjusting a semicircular wedge to match the slope of the hill, similar to a method developed by Proffitt et al. (1995). Although subjects viewed the slope head-on, the device depicted a side-view of the hill, requiring subjects to mentally make a 90^o yaw transformation. Following the slope estimate for each hill, distance estimates were collected using a magnitude estimation slider with lower and upper limits set to 0 and 100 meters, respectively. A 50 meter standard reference image was displayed at the start of the experiment. The initial positions of the slope and distance estimation devices were 0 degrees and 50 meters, respectively. Subjects adjusted the estimation devices using the scrolling wheel of a mouse and pressed the spacebar following each estimate. **Figure 6** illustrates the locations of the estimation devices and red box.

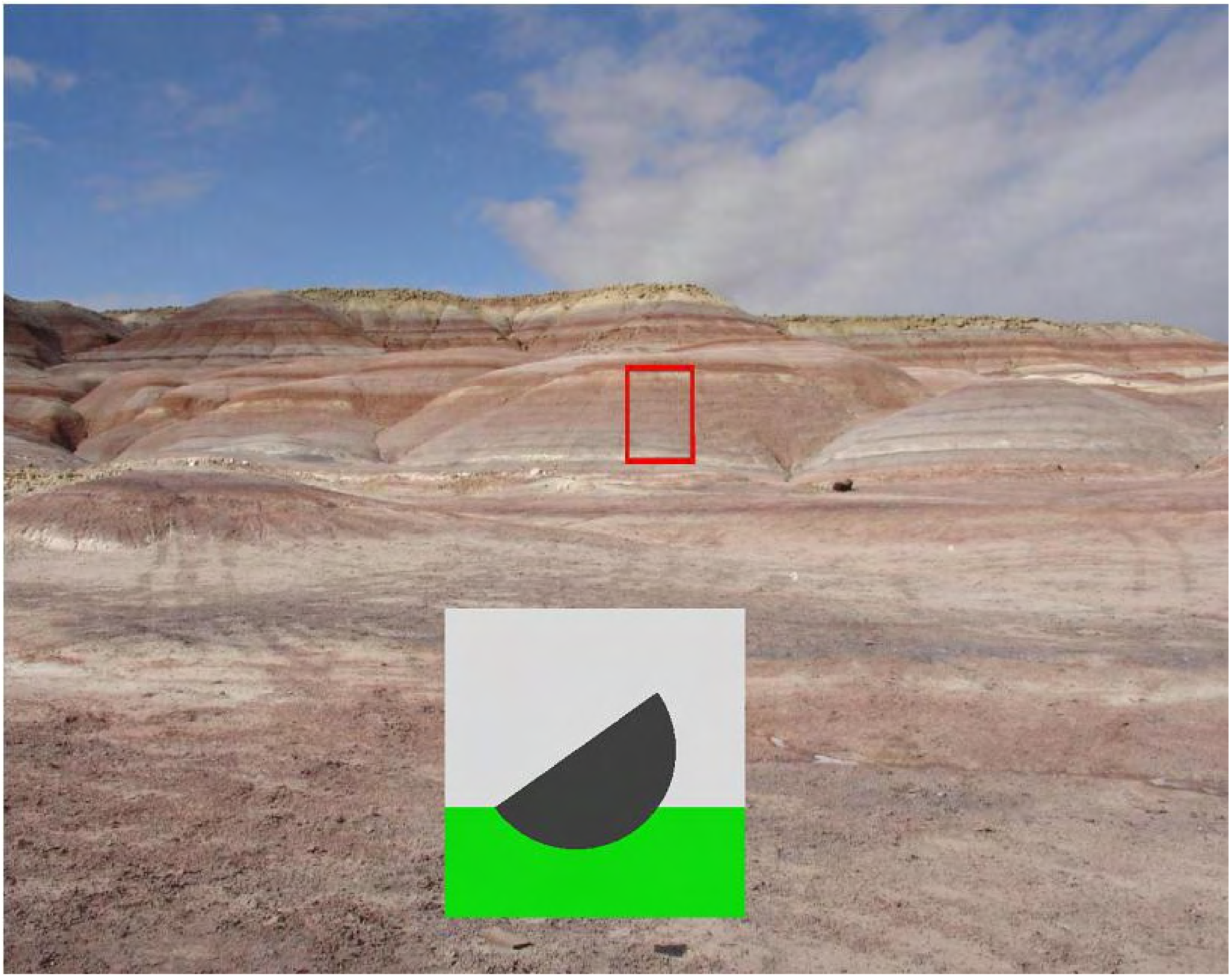

Figure 6. *Red Box indicating region to be estimated and location of estimation devices in MVS*

The LVS was divided into a training session and 5 test sessions. The training session presented images of two hills and two craters. The first and third test sessions displayed the 12 slope/distance combinations in a pseudo-random order that balanced any session effects of fatigue or improved performance. The second and fourth sessions contained the six lunar craters in a random order. The fifth session was a repetition of the six lunar hills (each hill at one distance condition), followed by the six lunar craters. The first, second, and fifth sessions were conducted in the standing position, while the third and fourth sessions were conducted in the supine support structure. Slope estimates were measured using the same device as in the MVS. Distance estimates to the lunar hills were measured using the device from the MVS with lower and upper limits set to 0 and 20.0 km, respectively, and increments of 0.1 km. The device was initially set to 10.0 km for each hill. Distance estimates across the lunar craters were measured using the same device with lower and upper limits set to 0 and 1500 m, respectively, and increments of 10 m. The device was initially set to 750 m for each crater. Height estimates were measured using a vertical scroll-bar magnitude estimation device with lower and upper limits set to 0 and 4000 m, respectively, and increments of 25 m. The device was initially set to 2000 m for each hill. Consistent with the MVS, the subjects pressed the spacebar to advance to each new image or estimation device. Rather than using a red box to indicate the region of the hill to be estimated, the LVS used two arrows, at the top and bottom of each hill or the near and far lip of each crater, to identify the region of the hill or crater to be estimated. Following the completion of each experiment, subjects completed a feedback form prompting them on the methods used and the factors affecting their estimates.

Statistical Analysis

A logarithmic or square root transformation of each measure was regressed using a categorical mixed regression with subject as the identifier to determine the factors that had a significant effect on the estimates. The residuals of each model were analyzed and tested for normality and homoscedasticity (uniformity of conditional variances). All factors were listed as fixed effects. Individual paired t-tests with a Bonferroni Adjustment compared the estimates between different conditions of each factor in the regression. The systematic biases of all combinations of significant factors for each estimate were calculated in both physical units (degrees or meters) and as a percent of the actual measure, and were compared to zero in a one-sample t-test. Standard deviations were found for each bias to represent the between-subject error.

RESULTS

The mean slope estimates, mean estimation bias (i.e., estimated slope – actual slope) , and the standard error of the bias are listed in **Table I** for the MVS and **Table II** for the LVS (hills only). In all experimental conditions, subjects clearly overestimated the slope of each hill. The bias increased as the slope of the hill increased and as the distance to the base of the hills decreased. These effects were statistically significant ($p < 0.0005$) in the mixed regression model of the log-transformed slope estimates with hill, distance from the hill, sun elevation, supine/standing position and session as fixed effects. In the post-experiment questionnaire, 60% of MVS subjects and 64% of LVS subjects commented that closer distances provided more visual cues, occupied a greater Field-of-View (FOV), and seemed taller, impressive, and intimidating. On the other hand, 25% of MVS subjects and 12% of LVS subjects reported that far away hills appeared like walls. Average slope estimates tended to be higher at the low sun elevation in the MVS. This effect was statistically significant ($p = 0.009$) in the mixed regression model. Sun elevation was not manipulated in the LVS. In the post-experiment feedback, many subjects reported judging slope using texture (35%) and shadows (25%), two cues that change dramatically with sun elevation. Finally, slope estimate biases were generally higher when made from the supine body position in both the MVS and LVS. The effect was stronger in the MVS ($p <0.0005$) than in the LVS ($p = 0.048$). Although the majority of subjects in both studies reported no noticeable effect of body position, many subjects did comment that slopes appeared steeper or that one's physical potential (the perceived physical effort a person is capable of exerting) was less in the supine position.

The mean distance estimates, mean estimation bias (i.e., estimated distance – actual distance), and standard error for each set of conditions are listed in **Table III** for the MVS and **Table IV** for the LVS (hills only). Distance estimates in both the MVS and LVS were affected by the hill slope and the viewing distance. As hill slope increased, there was a small but significant decrease in the distance estimates (MVS: $p = 0.001$; LVS: $p = 0.015$). Subjects tended to underestimate the longer viewing distances but overestimate the closer viewing distances. The sun elevation had a small but significant trend ($p < 0.0005$) for subjects to give smaller distance estimates in the MVS when the sun elevation is high (33 deg). The supine body position correlated with significantly greater distance estimates in the MVS ($p = 0.008$), but not in the LVS**.**

The mean height estimates, mean estimation bias (i.e., estimated height – actual height), and standard error for each set of conditions in the LVS are listed in **Table V**. The biases in height estimates ranged from -568 meters (underestimation) to 688 meters (overestimation) with large variability. The subjects' body position also did not have any effect on the height estimates. There was a significant effect of hill ($p < 0.0005$) and the height estimates were generally closer to veridical for the taller hills. Distance to the hill was not a significant factor. The data also suggests and small interaction effect between hill height and viewing distance. For small hills, height is overestimated at both distances. For the taller hills, subjects have a greater tendency to underestimate height at closer distances than at farther distances. This observation was not tested in the regression model.

The difference between the overall mean systematic slope bias for lunar hills and for lunar craters was calculated for each subject and compared to zero using a one-sample t-test. In all cases, the estimates were made of an "up-slope," either of the hill or of the far side of the crater. The estimated slope bias of lunar craters was found to be significantly greater than lunar hills by 5.3 degrees on average ($p < 0.001$). Post-experiment feedback support this result with 60% of subjects indicating that craters appeared steeper because they possessed greater texture, lacked a horizon for comparison, and possessed more indications of rock slide.

DISCUSSION

The slope overestimates were not unexpected, as they confirmed the results of previous studies conducted by Proffitt et al., among others (1995, 2001; Bhalla & Proffitt, 1999; Creem & Proffitt, 1998). Their results indicated a systematic overestimation of slope for verbal and visual measures over the population of subjects, but did not investigate the within-subject differences of the same hill under different conditions. This study expands knowledge of human slope estimation by showing that overestimates occur at a distance from the base of the hill and the amount of overestimation increase (larger errors) as either the distance or the sun elevation decreases. Although the experiments were conducted in a reduced-cue environment, the appearance and contrast of texture was more vivid as distance and sun elevation decreased, suggesting potential interactions between both distance and texture on slope estimates (closer distance makes texture more visible), as well as sun elevation and texture (lower sun elevations increase the contrast of texture). These interactions should be tested in future slope estimation studies.

The supine condition with lunar gravity loading is not a completely valid simulation of lunar gravity since the structure also adds tactile cues that would otherwise not be present. Subject comments about the supine condition suggest that they were able to discount or ignore the tactile cues, in which case, the results would support an effect of gravity. The results also could support Proffitt's hypothesis that one's physical potential affects their affordance to climb a hill, making it appear steeper (Proffitt et al, 1995). When lying supine, their estimate of the physical effort to walk up the slope might have been reduced due to less effort required to support themselves.

Under parabolic flight, Clement, Lathan, and Lockerd (2008) found that humans judged a 3D cube to be taller, thinner, and shallower in microgravity, thus the distance in the depth plane was underestimated. These results also suggest that a hill would appear steeper in microgravity and should be tested in future studies.

Previous distance estimation studies found estimates were influenced by the angular declination of an object (Ooi et al., 2001), binocular disparity and motion parallax (Beall & Loomis, 1995; Gogel, 1961), and the integration of the information in the ground plane leading to the object (Wu et al., 2004). The reduced-cue vast environment of this study made these methods inapplicable. Distance estimates were significantly different between hills due to numerous cues, including the hill height and the presence of familiar objects. The shortest hills in both studies received significantly greater distance estimates than all other hills, suggesting that subjects used the size-distance relationship and misinterpreted the smaller FOV subtended by these hills when compared to other hills.

The increased visual angle of a hill and the presence of surrounding objects likely influenced the significant effect of distance on distance estimates. The visual angle subtended by the MVS hills at a distance of 25 meters was over 9 degrees greater than the angle subtended at 75 meters. Subjects were not asked about their assumptions on the size of nearby objects, so the influence of this factor is unknown. The significant effect of sun elevation on distance estimates in the MVS was likely caused by the greater textural contrast of the ground plane and hills at lower sun elevations. The significant effect of the supine position on distance estimates in the MVS was potentially caused by the decreased physical potential, explained above, though the vast distances in the LVS likely minimized this effect.

The larger slope overestimation bias for lunar craters than for lunar hills confirms the hypothesis formed from a personal interview with Apollo 16 Astronaut Charles Duke (2008). This error is suspected to be even greater in lunar gravity, with the uncertainty of the down vector and the greater safety risk of being trapped within a crater.

The standard deviations of both the slope and distances biases were as great as or greater than the biases themselves, indicating that without training, it will be difficult to accurately predict the estimation performance of an astronaut preparing for a lunar mission. During Apollo 11, Astronauts Armstrong and Aldrin commented on size and distance estimation, insisting "these skills may require refinement in the lunar environment" (Heiken & Jones, 2007). The standard deviations of the biases support the need to develop a VR training tool for astronauts to use prior to a lunar mission. The purpose of this tool would be to expose astronauts to the slopes and distances they will experience to prominent landmarks and allow them to refine their estimates with or without the use of range-finding instruments and maps. Calibration would increase confidence in navigational instruments and may be necessary for emergencies if these instruments are not available or not operable.

Even with training of visual slope, distance, and size perception prior to lunar missions, astronauts will encounter unfamiliar terrain with unknown sizes and slopes. They may make erroneous judgments or become disoriented under certain environmental conditions. Integrating navigational instruments with a mathematical model that predicts estimation errors from the factors distorting human perception can increase awareness when illusions may exist. The proposed model design would include sun elevation, distance to the target terrain, sun azimuth, presence of shadows, textural contrast, surface slipperiness, and other factors as input variables and computes the estimated slope errors and estimate distance errors. If these errors breach specific thresholds, salient warnings should be displayed to the astronaut, warning him/her of the potential illusions. The MVS showed that both distance and sun elevation significantly affect slope and distance estimates, though only two conditions for each variable were tested. Future experiments should seek to identify the interaction these variables have with shadows, texture, height, and surface slipperiness and the regression coefficients for each of these continuous variables. Together, the use of a lunar VR environment to train and calibrate astronauts prior to missions and the integration of perception with navigational instruments will increase the safety and efficiency of future lunar missions.

ACKNOWLEDGMENTS

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ABBREVIATIONS

VR – Virtual Reality
MVS – Lunar-like VR Study
MDRS – Mars Desert Research Station
LVS – Lunar VR study
FOV – Field of View

LIST OF TABLES

Table I. Summary statistics of estimated slope for lunar-like hills in MVS

Position	Distance (m)	Sun Elevation (deg)	Actual Slope (deg)	Mean Estimate (deg)	Mean Bias (deg)	Stand. Err (deg)
Standing	25	10	14.3	28.2	13.9	1.5
			19.2	28.2	9.0	1.5
			22.8	34.8	12.0	2.5
		33	14.3	27.6	13.3	1.7
			19.2	28.3	9.1	2.1
			22.8	30.6	7.8	1.7
	75	10	14.3	24.6	10.3	1.2
			19.2	25.2	6.0	1.8
			22.8	32.0	9.2	2.3
		33	14.3	25.9	11.6	1.5
			19.2	24.1	4.9	1.8
			22.8	31.0	8.2	2.1
Supine	25	10	14.3	30.0	15.7	2.1
			19.2	30.3	11.1	1.8
			22.8	35.8	13.0	2.4
		33	14.3	28.3	14.0	1.7
			19.2	31.0	11.8	2.0
			22.8	33.0	10.2	2.3
	75	10	14.3	26.1	11.8	1.7
			19.2	28.7	9.5	2.3
			22.8	34.9	12.1	2.8
		33	14.3	28.6	14.3	2.2
			19.2	26.7	7.5	2.0
			22.8	29.9	7.1	2.3

Table II. Summary statistics of estimated slope for lunar hills in LVS

Position	Distance (m)	Actual Slope (deg)	Mean Estimate (deg)	Mean Bias (deg)	Stand. Err (deg)
Standing	Near	14.7	22.7	8.0	1.5
		15.1	20.6	5.5	3.0
		22.2	30.1	7.9	2.5
		24.1	29.0	4.9	2.0
		25.6	33.7	8.1	1.7
		25.6	33.7	8.1	2.4
	Far	14.7	21.8	7.1	2.4
		15.1	17.8	2.7	1.4
		22.2	31.5	9.3	2.0
		24.1	29.4	5.3	2.1
		25.6	31.0	5.4	2.8
		25.6	30.0	4.4	1.6
Supine	Near	14.7	24.0	9.3	2.4
		15.1	22.2	7.1	3.1
		22.2	30.3	8.1	2.6
		24.1	27.8	3.7	2.8
		25.6	35.3	9.7	2.5
		25.6	30.6	5.0	2.2
	Far	14.7	20.3	5.6	1.8
		15.1	20.0	4.9	2.4
		22.2	36.2	14.0	3.2
		24.1	30.8	6.7	2.2
		25.6	34.0	8.4	2.6
		25.6	31.8	6.2	2.5

Table III. Summary statistics of estimated distance for lunar-like hills in MVS

Position	Distance (m)	Sun Elevation (deg)	Actual Slope (deg)	Mean Estimate (m)	Mean Bias (m)	Stand. Err (m)
Standing	25	10	14.3	41.7	16.7	2.2
			19.2	34.4	9.4	3.0
			22.8	40.3	15.3	3.1
		33	14.3	42.9	17.9	2.7
			19.2	36.1	11.1	2.9
			22.8	33.3	8.3	2.7
	75	10	14.3	65.0	-10.0	2.7
			19.2	65.2	-9.8	2.9
			22.8	62.7	-12.3	3.0
		33	14.3	61.2	-13.9	2.9
			19.2	59.7	-15.3	3.1
			22.8	58.7	-16.3	2.9
Supine	25	10	14.3	45.1	20.1	2.5
			19.2	36.2	11.2	2.9
			22.8	44.2	19.2	3.2
		33	14.3	46.2	21.2	2.6
			19.2	35.2	10.2	2.9
			22.8	36.7	11.7	2.8
	75	10	14.3	67.7	-7.3	2.8
			19.2	64.2	-10.8	3.1
			22.8	65.0	-10.0	3.1
		33	14.3	59.7	-15.3	3.4
			19.2	61.7	-13.3	3.1
			22.8	64.8	-10.2	3.3

Table IV. Summary statistics of estimated distance for lunar hills in LVS

Position	Distance (m)	Actual Slope (deg)	Mean Estimate (m)	Mean Bias (m)	Stand. Err (m)
Standing	4000	15.1	8148	4148	841
	4300	25.6	5345	1045	494
	5000	22.2	5852	852	642
	5200	14.7	5324	124	379
	6500	25.6	7188	688	978
	8400	15.1	9843	1443	541
	8800	25.6	8721	-79	822
	9800	25.6	11294	1494	551
	10900	24.1	7282	-3618	439
	11400	14.7	9796	-1604	687
	11500	22.2	11490	-10	494
	13900	24.1	10352	-3548	910
Supine	4000	15.1	8696	4696	769
	4300	25.6	5936	1636	683
	5000	22.2	5300	300	503
	5200	14.7	4800	-400	564
	6500	25.6	7380	880	1060
	8400	15.1	10008	1608	848
	8800	25.6	8592	-208	764
	9800	25.6	11320	1520	853
	10900	24.1	7644	-3256	547
	11400	14.7	11472	72	693
	11500	22.2	11000	-500	761
	13900	24.1	9388	-4512	850

Table V. Summary statistics of estimated height for lunar hills in LVS

Position	Distance (m)	Height (m)	Mean Estimate (m)	Mean Bias (m)	Stand. Err (m)
Standing	4000	276	1014	738	156
	8400		817	541	96
	5200	700	1029	329	84
	11400		918	218	112
	5000	1110	1507	397	133
	11500		1462	352	98
	4300	1551	1976	425	124
	8800		1631	80	97
	10900	2091	1531	-560	97
	13900		1926	-165	136
	6500	2341	2224	-117	163
	9800		2362	21	104
Supine	4000	276	914	638	114
	8400		791	515	121
	5200	700	1030	330	130
	11400		915	215	109
	5000	1110	1514	404	118
	11500		1519	409	140
	4300	1551	2051	500	152
	8800		1682	131	135
	10900	2091	1507	-584	104
	13900		1890	-201	147
	6500	2341	2409	68	175
	9800		2448	107	137

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