Lunar Psychophysics:

Static vs. Dynamic Atmospheric Light Scattering on Perceptual Distortions in a Lunar Virtual Environment

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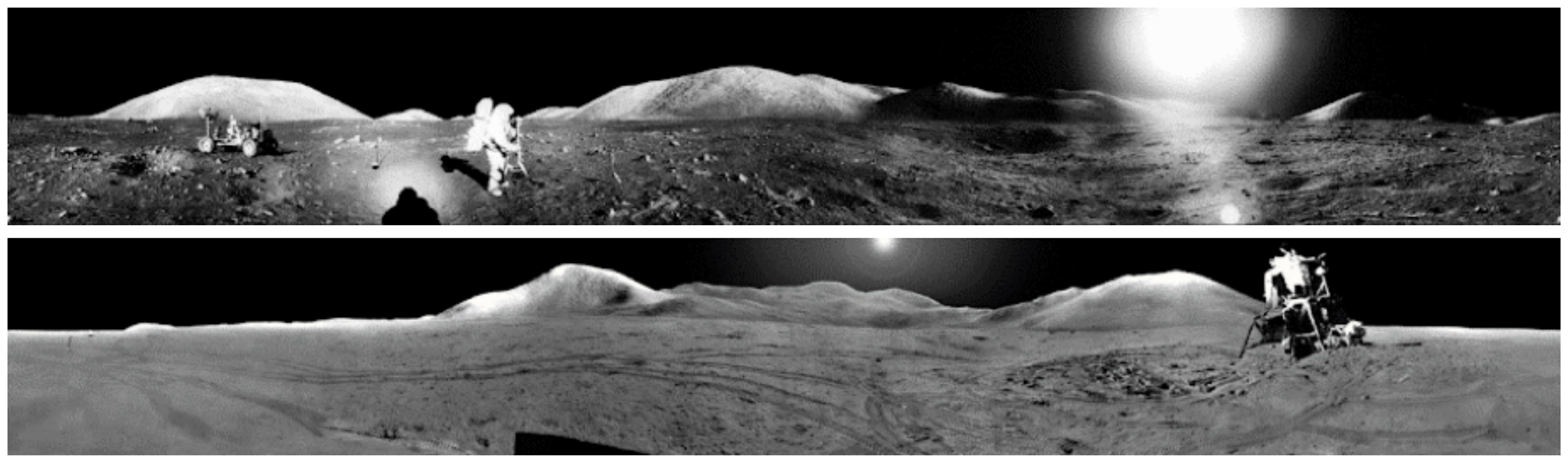
Abstract

This poster introduces a novel area of perceptual psychology that characterizes human perceptual capabilities in a lunar-like environment. This field of "***lunar psychophysics***" considers a range of visual, neurological and physiological sensory mechanisms of perception and their relationship to optical properties of light, atmospheric physics and psychophysics on the Moon. Two experiments assessed perceptual estimates of terrain (hills, mountains and craters) in 3 VE analogs with different atmospheric scattering and surface reflectance properties. Participants viewed these VEs with the Oculus Rift CV1 HMD in both Experiments. Future directions are discussed for expanding this model to understand perceptual capabilities for deep space asteroids and Mars.

Introduction

Upon landing on the Moon, the Apollo astronauts encountered an environment where the visual-sensory cues used for depth and distance perception on Earth were no longer reliable. Astronauts significantly underestimated the sizes of craters, hill slopes and distances to landmarks. While navigating the lunar surface, many faced unanticipated challenges when traversing lunar terrain, such as physical overexertion and the depletion of oxygen resources.

It is hypothesized that among the most critical sources of perceptual errors on the Moon are the unique reflectance properties of the lunar surface and the absence of an Earth-like atmosphere. The lack of an atmosphere, or "exosphere" causes dramatic changes in the scattering of light across the lunar surface. This can create deep shadows that limit depth perception, or it can backscatter across the surface, causing visibility to be lost altogether.



Figures 1 &2: NASA panoramic images showing the dramatic changes in light scattering across lunar terrain

Challenge #1: Since the end of the Apollo program, experiments on the capabilities of the visual system in space have been conducted in environments with which astronauts are most familiar. This has benefitted understanding of perception within small, compartmentalized areas of space. However, there is limited knowledge on how the differential properties of light outside of Earth's atmosphere affects human perception in extraterrestrial environments, and whether humans possess the sensory capabilities to respond appropriately to new forms of stimuli outside of Earth without adaptation.

Atmospheric Scattering

Rayleigh & Mie Scattering

Figure 3. Aerial (atmospheric) perspective on Earth.

Earth's atmosphere influences perception of relative distance via ***aerial perspective***. As an object's distance increases, the contrast between the object and its background become less apparent. Its color will begin to blend in with the background, which is usually blue.

When light strikes a range of small, non-absorbing spherical particles in Earth's atmosphere ***Rayleigh scattering*** results in the omnidirectional scattering across the surface which gives the sky its blue color and the Sun its yellow hue. ***Mie scattering***, occurs when light strikes larger spherical particles, resulting in non-uniform scattering observed in Earth's clouds.

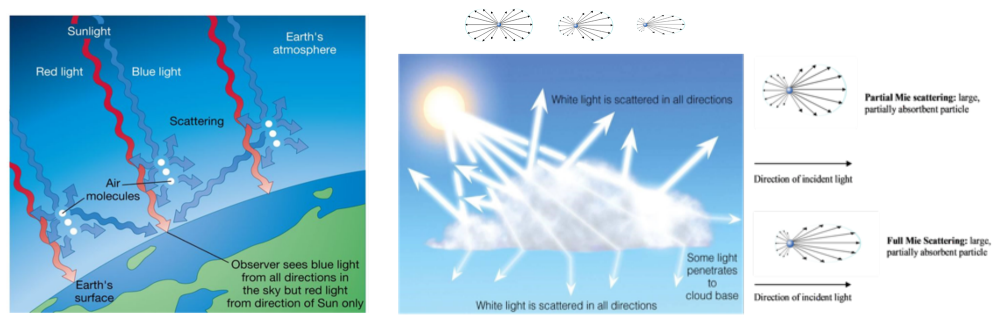


Figure 4. Rayleigh (small, nonabsorbent), Mie (small, partially absorbent), and Mie (large, partially absorbent)

Complex Particle Scattering

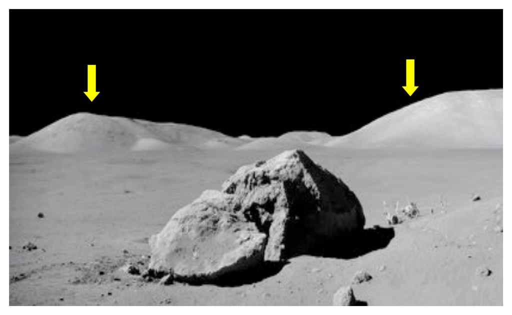


Figure 5. NASA image depicting a lack of aerial perspective in discriminating the distance to the Mons Vitruvius (left) and the South Massif (right) in the Taurus-Littrow Valley from Apollo 17.

The lack of an atmosphere and aerial perspective on the Moon limits the ability to differentiate distances between two landmarks. The increased clarity of distant objects makes them appear much closer, distorting estimates of distance.

This resulted in astronauts underestimating distances to craters or hills during navigation as documented across multiple Apollo missions. The moon's surface is comprised of a series of complex lunar dust particles (non-spherical grains that are non-uniform in composition) which can be used to simulate virtual conditions in which Mie scattering does and does not apply on the Moon.

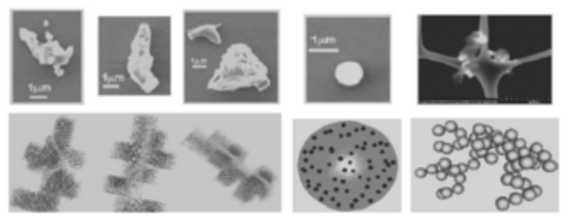
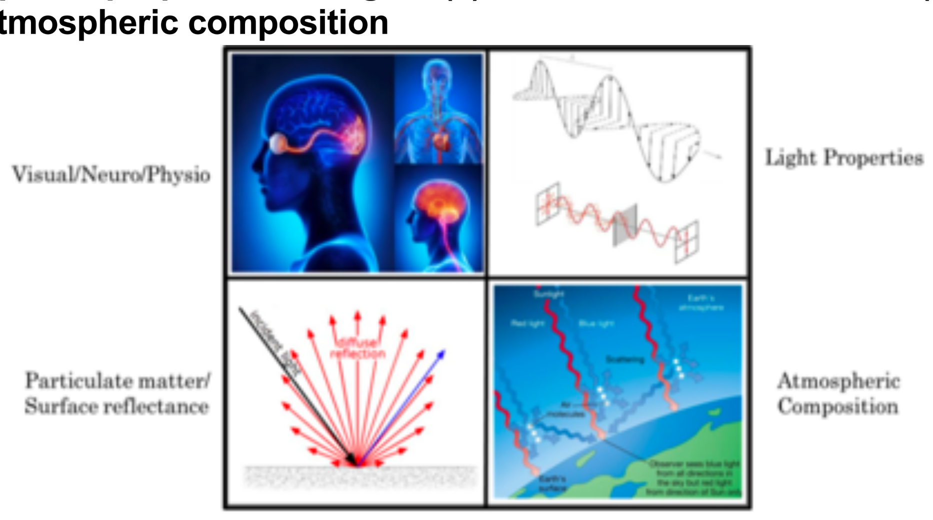


Figure 6. Electron micrographs of lunar dust grains from Apollo regolith samples (top row) and corresponding numerical models (lower row)

Lunar Psychophysics

Lunar psychophysics uses a multidisciplinary approach to examine both internal and external properties that contribute to perceptual problems on the Moon (Figure 7): **(1) visual, neurological, & physiological sensory mechanisms (2) the optical properties of light, (3) surface reflectance and (4) atmospheric composition**



The fundamentals of lunar psychophysics are derived from James J. Gibson's (1979) ecological approach to the structures of perception. While Gibson does not directly reference any theories of light scattering in his discussions of ecological optics and perception, his structural analysis of ambient light is similar to intrinsic properties of light relevant to Rayleigh scatter and CPLS models.

A goal of lunar psychophysics is to apply the functions of atmospheric scattering to understand perceptual distortions by referencing the location of the light source and an object relative to the observer. This is because visibility can change based on the intensity and direction of light relative to the observer and create inconsistencies in the visibility of an object's surface features.

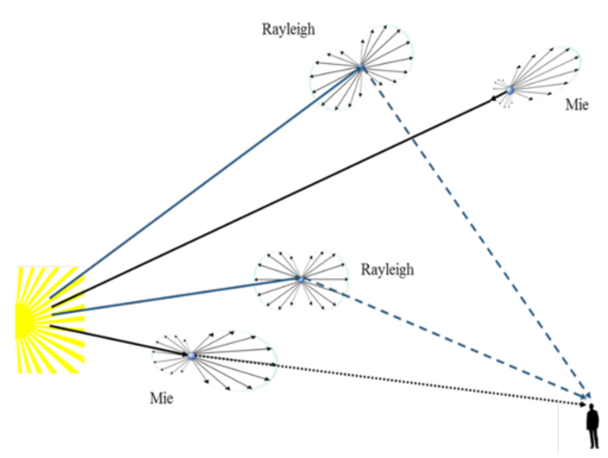


Figure 8 is a conceptual illustration showing different hypothetical objects in the sky with different reflectance properties: Rayleigh (small particulate matter) and Mie (larger particulate matter). The two Rayleigh objects (blue dotted lines) objects illustrate a uniform distribution of reflectance that reaches the observer in a consistent, perceivable wavelength (blue)

Rendering Planetary Atmospheres: VE Analogs

To create a realistic, accurate representation of the visual effects of light scattering on Earth and the Moon, each of these VR models were modified as needed by adjusting the following variables in Unity 3D: Rayleigh scatter/extinction coefficients, Mie Scatter/extinction coefficients, shaders, atmosphere height and density, sun elevation and intensity, density scale and height of terrain.

Fig 9. Earth (right), Lunar-Earth Hybrid (center) and Lunar (right) analog craters by Rahill (2019)

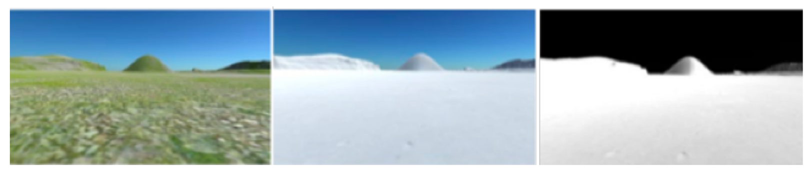


Fig 10. Earth (right), Lunar-Earth Hybrid (center) and Lunar (right) analog hills by Rahill (2019)

Hypotheses

EXPERIMENT 1

Aim 1: Examine differential effects of atmospheric light scattering across 3 VE analogs

- **Hyp 1**: Perceptual accuracy in Earth-Rayleigh VE ~ Lunar-Rayleigh VE > Lunar-CPLS

Aim 2: Determine optimal degree of sun elevation in lunar CPLS analog (Figure X, right)

- **Hyp 2**: 30º, 60º and 90º (Exp 1) → optimal 30º (Exp 2)

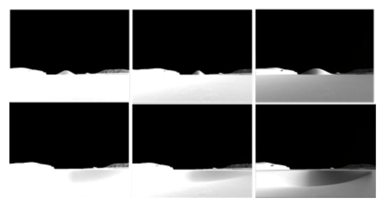


Fig 11. Lunar terrain in 30º (left) 60º (center) and 90º sun elevation; Rahill (2019)

EXPERIMENT 2:

Aim 3: Perceptual accuracy will increase in VE analogs that are dynamic (i.e. Exp 2)

- **Hyp 3**: Performance in Dynamic (Exp 2) > Static (Exp 1)

Aim 4 : Dynamic interactions with light scattering will improve perceptual accuracy Lunar VE analogs

- **Hyp 4:** Perceptual accuracy in experiment 2 > Exp 1 due to translational optic flow cues in the environment

Results

Experiment 1 (Static Atmospheres): N=70 (W-Ss) participants; stood in a stationary position while viewing images of terrain in 30º, 60º and 90º sun elevation, which identified potential interactions between sun elevation (time of day) and atmospheric light scattering on perceptual distortions.

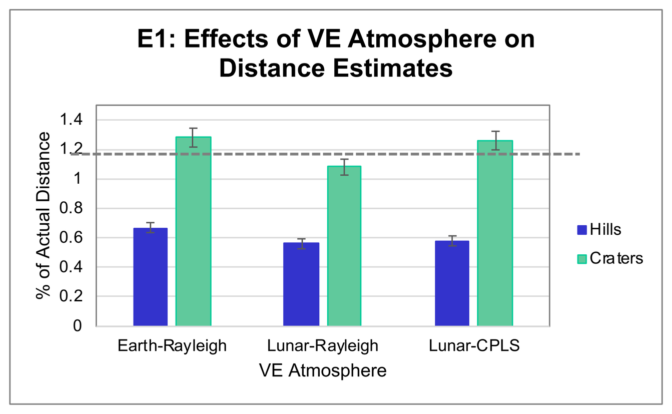


Figure 12. Means and standard deviations of hill and crater distances; p<.001

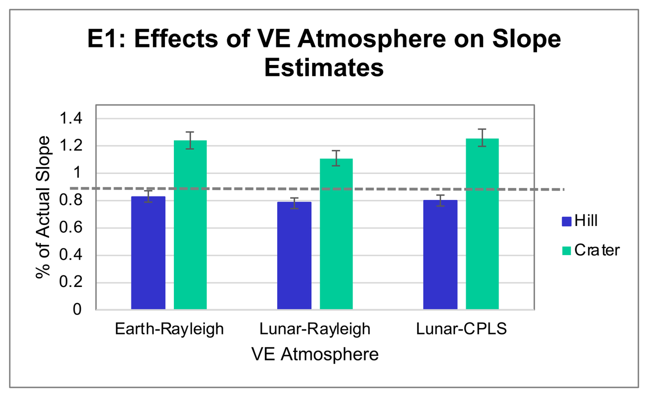


Figure 13. Means and standard deviations of hill and crater slopes; p<.001

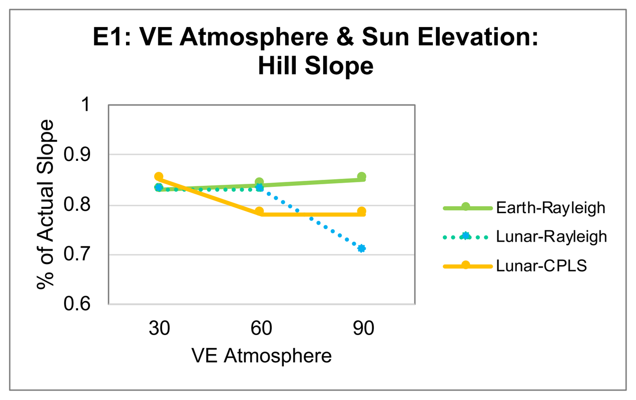


Figure 14. Static atmosphere and slope interaction; p<.05

Experimental 2 (Dynamic Atmospheres): N=60 (W-Ss) participants; examined the perceptual distortions of dynamic images of terrain in all 3 VEs while navigating a lunar rover in the optimal degree of sun elevation (30º) found in Study 1.

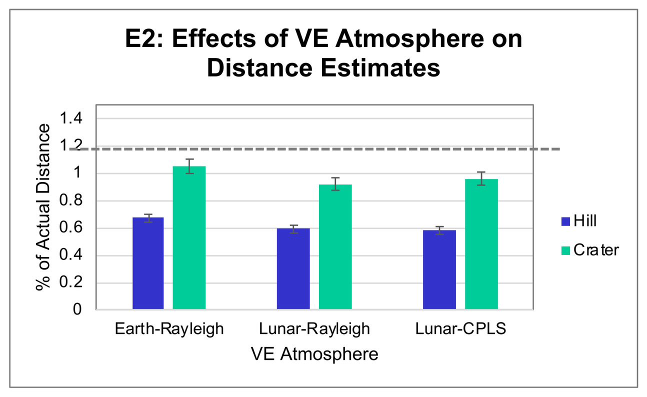


Figure 15. Means and standard deviations of hill and crater distances; p<.05

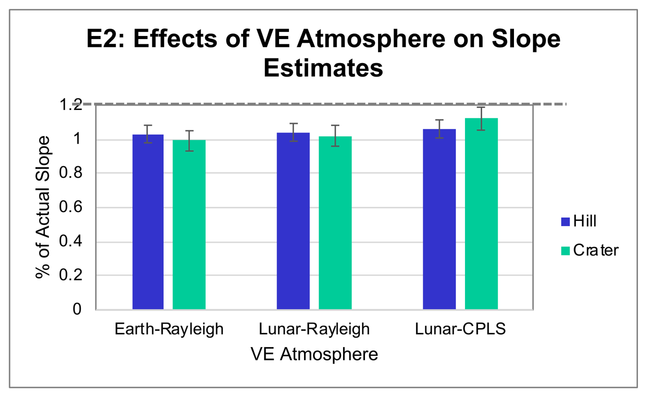


Figure 16. Means and standard deviations of hill and crater slopes; p<.05

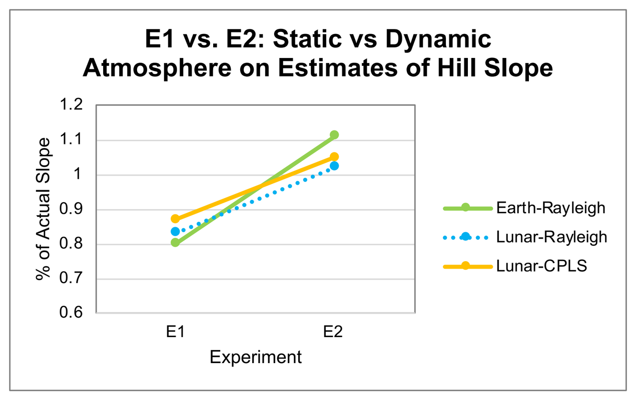
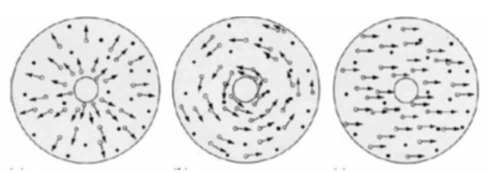


Figure 17. Comparison of hill slope accuracy between Exp 1 and Exp 2; p<.05

Discussion

Atmospheric Scattering: As predicted, the **Earth VE analog elicited in the most accurate estimates** across both experiments. The addition of an Earth-like atmosphere on the Moon **provided compelling evidence to suggest that Earth's atmosphere *alone* is not an invariant feature of perception** due to other ecological features (e.g. surface reflectance) in the environment.

Sun Elevation: Significant variation across the 3 VE analogs, suggesting that perception will ***change* on different planets contingent upon time of day.** Surface textures may be able to provide sufficient information about distance and slope on the Moon, but this is contingent upon the **location of the observer relative to the object and the location of the sun relative to the two objects**. The sun was placed in an ideal location (cross-sun position) as noted by astronauts for being optimal viewing conditions on the Moon.



Kinetic Depth: The role of kinetic depth in Exp 2 was not present in Exp 1. It's possible that the process of approaching a landmark or object changed their perception of physical effort or physiological state during motion; thereby improving perceptual accuracy. **Figure 18 (left)** shows a schematic representation of the different types of optic flow components which are afforded by invariant properties (light and surface reflectance) **present in Earth environments**: Radial rotation (left); Rotational motion (center); Translation (right).

Perceptual Learning: Results also suggest that individuals use different visual cues (light scattering/surface textures) depending on whether a landmark sits above (i.e. hill) or below (i.e. craters) the horizon in the visual field.

Challenges & Implications

Challenge #2: Need for a "representative", astronaut-like sample. Improvements in an "expert-like" sample would most likely be seen in the learning process of adapting to novel stimuli and learning to navigate and traverse terrain more efficiently (i.e. expeditionary behavior).

However, if conditions were beyond the spectrum of visibility, improvements may not be seen. Therefore, it is plausible that vision could be further distorted when exposed to dramatic, long term changes in the intensity of light scattering conditions on the Moon.

Challenge #3: Microgravity and transfer of training: experiments are limited to visual effects of microgravity vestibular stimulation is replicable but other physiological effects are limited; need for increase tactile realism.

Next Steps: Martian & Exoplanetary Psychophysics

Martian psychophysics: need for more interactive VR simulations to recreate the visual effects of light scattering on other planets, such as Mars, to expose astronauts to the types of unfamiliar stimuli they will encounter and have them perform similar perceptual tasks in these conditions they would need to accomplish on a mission.

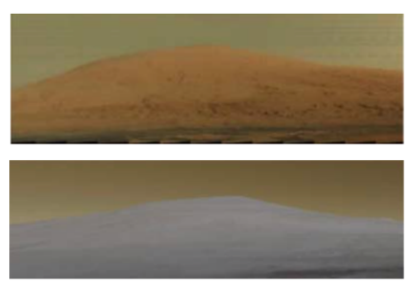


Figure 19. Martian terrain (top) and VR rendering (bottom); Collienne (2016).

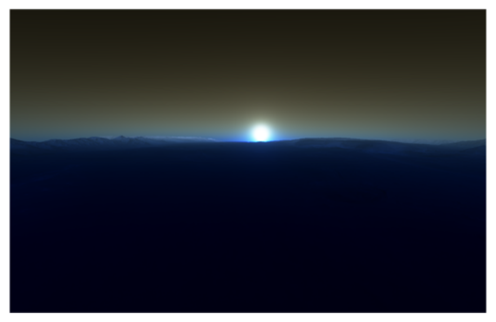


Figure 20. Martian atmosphere: rendering of inverse visual effects of Rayleigh scattering; Rahill (2019)