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The Effects of Ambient Light Intensity on Affordance Perception

Tyler Overstreet

THE EFFECTS OF AMBIENT LIGHT INTENSITY ON AFFORDANCE PERCEPTION

by

Tyler Ryan Overstreet

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Committee:

Dr. Alen Hajnal, Committee Chair
Dr. Nuno Oliveira
Dr. Jonathan Doyon
Dr. Aaron Fath

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ABSTRACT

Humans can reliably perceive whether a slanted ground surface can be stood on or not. In the present study we investigated how differences in ambient lighting conditions affected the perception of stand-on-ability. The study manipulated lighting conditions (photopic, mesopic, scotopic) under which participants made affordance judgements about the stand -on-ability of a presented ramp in a virtual reality environment. We hypothesized that less visual information would be available in the scotopic condition, which would result in changes to affordance boundaries and movement complexity, when measured from head sway and center of pressure. Results indicated that participants' affordance judgements were more conservative in low lighting and that movement complexity decreased at the affordance boundary. In addition, we showed that affordance responses can be predicted by movement complexity. The study demonstrated that exploratory activity exhibited through postural adjustments of the body generates information that specifies affordance perception.

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LIST OF ABBREVIATIONS

COP	Center of Pressure
CV	Coefficient of Variation
ETC	Effort-to-Compress
IRB	Institutional Review Board
lx	Lux
MFW	Multifractal Spectrum Width
VR	Virtual Reality

CHAPTER I – INTRODUCTION

Functional behavior takes place in a cluttered environment that is illuminated by complex light patterns. It is unclear how light intensity influences affordance perception (Blanchard et al., 2007; Brooke-Wavell et al., 2002; Kinsella-Shaw et al., 2006). The present study investigated the influence of ambient light on perception by manipulating lighting conditions while participants made affordance judgements about the stand-on-ableness of a ramp in a virtual reality environment. Optic flow (Gibson, 1950) provides visual information to guide behavior and perception in tasks where vigorous movements (such as locomotion) are involved to navigate obstacles (Warren, 1984), and gaps (Fath & Fajen, 2011; Lucaites et al., 2021; Warren et al., 2001). In tasks where the observer is stationary, exploratory activity via postural sway generates more subtle optic flow patterns. Past research has shown that nonlocomotor exploratory activity is related to perceptual judgments of affordances (Hajnal et al., 2018; Mark et al., 1990; Masoner et al., 2020; Stoffregen & Yang, 2005; Yu et al., 2011). The goal of the present study was to test which movement parameters of postural sway (if any) serve as significant predictors of perceptual judgments, and how those interact with changes in the visual environment. The results from this study have the potential to aid in describing the role of exploration in affordance perception.

1.1 Optic Flow and Postural Control

Postural control relies on perception of the layout of surfaces in the environment to maintain stability. A large body of literature has shown that visual information influences postural stability (Hajnal et al., 2014; Hajnal et al., 2022; Lishman & Lee, 1973; Stoffregen et al., 1999). Optic flow describes how visual patterns change in a visual scene relative to a moving perceiver. For example, as the perceiver moves forward through space, the optic flow moves outward away from the center of the visual field causing the optic array to expand. When the perceiver is moving backwards through space, the optic flow moves towards the center of the field causing the optic array to contract. Dijkstra et al. (1992) discovered that when attention is focused on nearby objects, the optic flow patterns are larger and more detailed, thus providing more precise information for maintaining postural stability. In principle, even a small displacement of the body can create relatively large changes in optic flow in near space depending on the speed of the movement. Optic flow in near space is especially relevant for the control and guidance of actions and should therefore play an integral role in affordance perception.

There is a large body of literature on how surfaces in the optic array influence posture (Lishman & Lee, 1973; Stoffregen et al., 1999; Simeonov et al., 2003; Simeonov et al., 2009). Lishman and Lee (1973) demonstrated that the presence of a vertical surface in close proximity in front of the observer has a dramatic impact on stabilizing posture via visual information in the optic array. Stoffregen et al. (1999) showed that nearby targets make posture more stable compared to looking at distant targets or no targets at all. This effect is also present when the perceiver is standing on an inclined surface: Simeonov et al. (2003) found that posture becomes more stable when looking at a vertical reference object such as a vertical bar while standing on an inclined roof. This finding was elaborated on by Simeonov et al. (2009) who showed the effect becomes more pronounced when the object is placed nearby. This evidence suggests that objects and surfaces in the environment serve as visual anchors that aid in maintaining balance during upright stance.

Postural control appears to depend on the distance of objects and surfaces in the optic array. Bonnet et al. (2010) explicitly tested the effects of proximity of objects on postural stability and found that the presence of objects nearby provided the most stability. Focusing on a target (in this case a dot on a wall) in the presence of other objects (such as a large box placed at various distances) creates complex optical structure, that provides rich information for affordances that are relevant for a specific task or goal. Task relevant affordances relate to the idea of suprapostural goals, or goals that are superordinate to the control of posture (Stoffregen et al., 1999). Stable posture is necessary to achieve many behavioral goals (Gibson, 1979; Turvey, 1990). Therefore, nearby objects may aid in the achievement of a superordinate goal by serving as "visual anchors" stabilizing posture.

In addition to target distance from the observer, surface angle and task have also been shown to affect postural stability. Hajnal et al. (2014) discovered that the presence of a flat surface at a steep angle in front of an observer during quiet stance stabilized posture and increased movement complexity, a measure of postural sway, when standing on a horizontal surface. Missing from their experimental design was a functional task and furthermore, it was unclear if the effect was due to the angle of the surface slant, distance from the observer, or both. Subsequent empirical investigation by Hajnal et al. (2022) indicated that both distance and angle influenced perception via the moderating effects of movement parameters in a task-dependent manner. Specifically, postural stability was influenced by the surface slant and distance from the observer. More interestingly, head sway parameters predicted affordance judgements in the affordance task but not in the nonfunctional task (angle estimation), indicating that the functional nature of the task, not the mere presence of the surface in the optic array affects postural stability. These results stress the importance of distance, orientation, and having a well-defined functional task on postural stability.

1.2 Postural Sway as Exploratory Activity

Although subtle, head- and postural sway can serve as exploratory movements since head sway creates optic flow patterns that contain specifying information about potential actions (affordances). In fact, Gibson (1979) has claimed that exploratory movements are necessary for the detection of information that guides perception. These exploratory movements can be large, such as walking, or small such as subtle postural sway.

What is the best way to characterize the exploratory activity of the body during the maintenance of upright stance? Multifractality is a complexity measure borrowed from statistical physics that is often used to quantify movement variability (Kantelhardt et al., 2002; Chhabra & Jensen, 1989). Multifractal signals exhibit high interactivity among different timescales of measurement, whereas less multifractal signals reflect more homogeneous variability and less interactivity at all scales of measurement. Highly multifractal signals are oftentimes described as complex (Shimizu et al., 2002). In addition to multiscale interactions, another feature of complexity is the richness of the structure of variability. The more varied and unique patterns are contained in the signal, the more complex it is said to be. Both aspects of complexity (high interactivity across scales and the variety of patterns) indicate that the signal is nonstationary, meaning its mean and variance change over time. Therefore, nonstationary signals are best characterized in terms of complexity rather than mean and standard deviation. Further, there is evidence that measures of complexity are more useful at predicting affordance judgements than measures of central tendency and spread (see Kelty-Stephen et al., 2013 for review).

Several studies have provided evidence that exploratory movements, characterized by multifractality, can predict perceptual responses in affordance tasks (Doyon et al., 2019; Doyon et al., 2021; Hajnal et al., 2018; Masoner et al., 2020). Hajnal et al. (2018) conducted an experiment in which participants observed a ramp while standing still. During observation participants made “yes” or “no” affordance judgments while head motion was measured. Results indicated that multifractality was a strong predictor of affordance judgments, above and beyond the contribution of standard deviation of head motion. Specifically, postural sway exhibited complex movements, meaning that the variability in movements was not uniform across time scales.

Doyon et al. (2019) showed significant interactions between multifractality of postural sway and affordance responses, specifically the use of visual information to calibrate haptic judgements through touch. In one condition, participants felt a small, occluded surface set at a discrete angle with their foot and attempted to match it visually to a larger adjustable surface. In another condition, participants adjusted the small slanted surface haptically in an attempt to match its slant to the larger visible surface. The researchers concluded that the multifractality of exploratory behavior predicted affordance judgements regardless of which energy array type was available for exploration.

Doyon et al. (2021) conducted four experiments investigating the role of variables related to the exploratory activity of head movements in a reaching affordance task in virtual reality. Results indicated that variables related to complexity such as multifractality of head movements fit a predictive model of perception better than variables related to static physical constraints of the task. In sum, there is growing empirical evidence that perception is informed by rich exploratory activity, and that exploratory activity enables the detection of functionally relevant information through complex interactions across scales.

1.3 Influence of Ambient Light on Postural Sway

The optic array changes as a function of exploratory activity and due to changes in the environment. One way the environment changes is through differences in illumination. Exploratory activity occurs under conditions where ambient energy patterns (e.g., reflected light) change continuously. How do different intensities of illumination influence exploratory activity and in turn perception of affordances? Under photopic conditions the eye detects light patterns in a well-lit environment, typically occurring naturally outdoors during the day or in an artificially lit building. Scotopic vision occurs under low light levels, typically experienced on a moonless night with no artificial lighting. Mesopic vision is at a level between photopic and scotopic vision. It is present in low, but not quite dark lighting conditions, for example, a suburban neighborhood street at night (Stockman & Sharpe, 2006).

There are a limited number of studies that have investigated the effects of lighting conditions on postural stability. Brooke-Wavell et al. (2002) found that postural sway was greatest in dim light (1 lx) during quiet upright stance compared to moderate (10 lx) and bright light (186 lx) conditions but was less than when the eyes were closed. The results suggest that low lighting conditions decrease stability but that visual information, even in extremely dim lighting, stabilizes posture more than no visual information (0 lx) at all. This effect seems to be absent in children, who appear to have better night vision. Blanchard et al. (2007) showed no difference in postural sway between regular (200 lx) and dim (3 lx) light in children aged nine to eleven. Perhaps the most comprehensive study on lighting's influence on postural sway was done by Kinsella-Shaw et al. (2006) which compared postural sway in two lighting conditions (3 lx, 440 lx) between older adults (aged 65-82 years) and younger adults (aged 22-24 years). They also manipulated the visual environment by having the participants attend to either a vertical collection of aluminum rods (providing rich optical structure) or a blank wall. The results indicated that reduced environmental structure (blank wall), and reduced illumination (3 lx) decreased postural stability, more so in older adults than in young adults.

Besides the lack of empirical studies on the influence of illumination on postural stability, there are other limitations to the existing literature. The previous studies have focused on older populations during a nonfunctional task. There is justification for this, because falling can be highly detrimental for the older population and their stability appears to be diminished even more so in dim light. However, because these studies lack functional tasks, there is no way to draw conclusions about the influence of lighting and postural sway on affordance judgements and behavior. The scarcity of empirical studies on the influence of illumination on postural stability, and even more so, on affordance perception warranted the current investigation. Therefore, the present study will aid in the understanding of the relationship between affordance perception, exploration, and light. We wanted to find out if decreasing light intensity makes affordance judgements more conservative and if perceivers exhibit more postural sway in order to detect affordances.

These results could have implications for designing safer well-lit environments and developing immersive virtual reality environments.

1.4 Present Study

In the current study, we measured participants' affordance judgements on whether they can stand on a presented ramp ranging from 0° to 90° in virtual reality. During quiet stance force plate position data was recorded from under the feet, along with head sway via the virtual reality headset. Various measures of postural sway and head sway (mean magnitude, coefficient of variation, complexity) were calculated during each trial under normal lighting (photopic), low lighting (mesopic), and dark (scotopic) conditions. In order to have precise control over the lighting condition, the study took place in virtual reality (VR). Several studies have shown that affordance judgements remain accurate in VR (Guess et al., 2016; Masoner et al., 2020; Baggs et al., 2024). Guess et al. (2016) had participants judge if they could cross a gap in VR. They found that there was no difference in the accuracy of judgments between the real-world and VR. Perception of the affordance for reaching has also been shown to be comparable in both the real-world and VR (Masoner, et al., 2020). Baggs et al. (2024) conducted an analysis of the literature on visual information in VR and concluded that VR simulates an ambient optic array that allows for detectable affordances.

We hypothesized that the scotopic and mesopic lighting conditions would result in diminished perception. We assumed this would be caused by less photons entering the eye per second, thus providing less optical structure needed to accurately judge the affordance of stand-on-ability. As a consequence, suboptimal illumination should make the task harder, and therefore cause affordance judgements to be more conservative and slower as well as lead to the perceivers exhibiting more complex postural sway in order to detect more information.

Affordance judgements becoming conservative will be based on observed changes to the average transition point at which participants report “yes” to stand-on-ability to “no”. This transition point is called the affordance boundary. Previous literature has shown that the typical affordance boundary at which a surface is no longer stand-on-able is around 30 degrees (Malek & Wagman, 2008; Hajnal et al., 2018). If affordance judgements are hypothesized to be conservative in the scotopic condition, then we should expect an affordance boundary less than 30 degrees.

Additionally, research has shown a significant increase in response time at the affordance boundary (Doyon et al., 2019; Hirose & Nishio, 2001; Lopresti-Goodman et al., 2009; Richardson et al., 2007; van der Kamp et al., 1998). This is perhaps best explained by understanding perception-action as a self-organizing dynamical system (Kelso, 1995). In such systems critical fluctuations tend to occur at transition points, and these transition points are associated with longer response times.

Finally, we hypothesized that affordance perception should be predicted by movement complexity based on previous literature (Doyon et al., 2019; Doyon et al., 2021; Hajnal et al., 2018; Masoner et al., 2020). We suspect that various measures of complexity will significantly interact with lighting and slope angle.

The underlying assumption running through our hypotheses is that exploratory activity generates information via complex movement patterns. As such, postural sway is integral to the detection of information in functional tasks. The conceptualization of postural sway as exploratory activity (Stoffregen et al., 2005; Yu et al., 2011) goes counter to traditional accounts that see increased postural sway as an indicator of instability and a source of noise.

1.5 Hypotheses

Hypothesis 1. The affordance boundary in the scotopic condition was expected to be significantly less than 30 degrees

Previous literature has shown that the typical affordance boundary at which a surface is no longer stand-on-able is around 30 degrees (Malek & Wagman, 2008; Hajnal et al., 2018). As light intensity decreases, the affordance boundary for the affordance task should decrease, if participants are more conservative with their affordance judgments in low lighting. This may indicate that observers are more cautious in order to prevent potential falls from sloped terrain in the dark, or that the information that specifies accurate perception is lacking or difficult to detect.

Hypothesis 2. The affordance boundary in the scotopic condition was expected to be significantly lower than in the mesopic and photopic conditions

Relatedly, there should be no significant difference in the affordance boundary between mesopic and photopic lighting conditions. Rods and cones are both active in photopic and mesopic lighting, whereas mostly rods are active under scotopic light conditions (Zele & Cao, 2014). Therefore, visual acuity should be sharp enough to make reliable affordance judgements under photopic and mesopic conditions but diminished under scotopic light, due to the availability of less optical structure to detect the affordance. This hypothesis is consistent with Duplicity theory (Stabell & Stabell, 2009) according to which cones are important for high visual acuity and color vision, whereas rods are optimal for night vision. Since the optical structure is revealed dynamically through the generation of optic flow, adequate visual acuity is necessary to detect subtle changes in said structure (Pan & Bingham, 2013). The difference in perceived brightness between scotopic and mesopic light is bigger than between mesopic and photopic light, because at dim lighting the pupil is wide open letting in disproportionately more light. Due to this, the relationship between illuminance (measured in lux) and perceived brightness is typically nonlinear. Thus, we expected no significant differences between mesopic and photopic light conditions.

Hypothesis 3. Reaction time should be significantly longer in the scotopic condition compared to the photopic and mesopic conditions

As light intensity decreases, reaction time should increase due to the stand-on-ability task becoming more difficult in the darker conditions, potentially requiring more time for exploratory activity.

Hypothesis 4. Complexity, and not mean magnitude or variability, of head- and postural sway should be significantly higher in the scotopic condition compared to the photopic and mesopic conditions

As light intensity decreases, complexity should increase due to the increase in exploratory movements in an attempt to detect the information that specifies the affordance.

Hypothesis 5. Light intensity and complexity measures of exploratory body sway should interact significantly in predicting affordance judgments

Dimmer lighting should result in a diminished and impoverished visual array, thus forcing the observer to use enhanced exploratory activity from head sway and COP to generate more distinct changes in optic flow. Specifically, a significant interaction between light intensity and complexity parameters was expected, such that more complexity should be employed under dim lighting condition to facilitate the detection of information that specifies stand-on-ableness.

CHAPTER II – METHOD

2.1 Participants

Participants (n = 31) were recruited from the Psychology Department's SONA Research Participant Pool for extra credit in their psychology courses at the University of Southern Mississippi. Based on past research (Hajnal et al., 2014; 2022), and the expectation of medium to large effect sizes, the sample size was adequate to achieve sufficient power (0.8). In order to ensure the virtual reality (VR) system is calibrated correctly for each participant's body proportions, eye height was recorded before the experiment began for each person. All experimental procedures were approved by the local Institutional Review Board (IRB) in accordance with the Declaration of Helsinki on the ethical treatment of human subjects in research.

2.2 Apparatus

The experiment was designed and displayed in the Unity game engine software (v2017.1.1fl) running on Windows 10 and used C# programming language to script events and commands. The virtual reality system was an Oculus Rift head mounted display and two hand-held controllers for making responses. The virtual environment displayed ramps at varying angles, covered in a green grass-like texture that were located on the floor in a large grey room. The base of the ramp was 1 m (*Figure 1*) away from the participant's feet to allow for a clear sight of the whole surface while still being close enough to be relevant for the potential action of stepping onto the surface. Each lighting condition featured a directional light source located at the top of the room halfway between the participant and the ramp. Directional light was chosen because it produced perfectly parallel light rays that do not diminish in intensity and is often the light type chosen to be a stand-in for natural sunlight (Unity Technologies, 2020). The light source provided diffuse lighting since it was not a spotlight, meaning that it did not create high contrast boundaries between dark and bright locations in the room. While the participants wore the VR headset, they stood on an AMTI force plate that recorded postural sway.

Physical properties of light can be measured in multiple ways (i.e., lumen, candela, or lux). Lumen measures the quantity of light that is emitted from the source, candela measures the intensity of the light in a given direction, and lux measures the quantity of light on a given surface. Since this study was concerned with the brightness of the surface of the ramp in the visual array, lux appeared to be the best measure of light intensity. Additionally, we remained consistent with past studies, since researchers examining the effects of lighting on postural stability have used lux to measure light intensity (Kinsella-Shaw et al., 2006).

Using the High-Definition Rendering Pipeline within Unity, the photopic condition was set at 440 lx (about the brightness of a typical office with overhead lights), the mesopic condition was set at 3 lx (suburban neighborhood at night), and the scotopic condition was set at 1 lx (outside on a moonless night) on a logarithmic scale, consistent with environmental lighting standards (New Building Institute, 2003; Mutmansky et al., 2010).

2.3 Design and Data Analysis

Dependent measures included response time, yes/no responses about stand-on-ability in the affordance task, force plate movement parameters of center of pressure (COP), and head movement parameters computed from recordings by the VR head mounted display as spatial coordinates of head motion (x, y, and z coordinates in meters).

COP was examined using mean magnitude, coefficient of variation (CV), effort-to-compress (ETC), and multifractal spectrum width (MFW), while head movements were examined using all the above except MFW, due to not meeting minimum time series length requirements for reliable computation of the parameter value (Kirichenko et al., 2020; Lopez & Contreras, 2013). The head position data was captured at a sampling rate of 80Hz, whereas the force plate measurements were sampled at 1000Hz. Head sway trajectories and COP fluctuation time series were converted into one-dimensional Euclidean distance time series for each trial by taking the arithmetic distance between each subsequent coordinates of the trajectories. This is equivalent to taking the first derivative of the original time series. The absolute value of the Euclidean series was used to calculate all the movement parameters of head sway and COP fluctuations. Independent measures were ramp angle (0° to 45° in 5° increments, and then 45° to 90° in 15° increments) and lighting condition (photopic, mesopic, and scotopic, control). Not many "Yes" responses were expected for ramps over 45° (because the average affordance boundary is 30°), thus the angles increased in larger increments past that point.

The perceptual boundary was calculated for each person and each lighting condition separately following the procedure from past research (Hajnal et al., 2016; Malek & Wagman, 2008; Wagman & Hajnal, 2014). First, the steepest angle at which the participant responded with a "yes" on at least 2 out of 3 repetitions of the same stimulus slope was identified. Second, the perceived affordance boundary was computed as the average between this angle and the next higher increment. For example, if the steepest angle at which at least 2 "yes" responses were obtained was 20°, then the perceived affordance boundary was computed as (20+25)/2=22.5°.

We employed a 3 Light Intensity (photopic, mesopic, and scotopic) × 13 Angle factorial experimental design. For Hypothesis 1, we computed 3 one-sample t-tests comparing the perceived affordance boundary in each lighting condition with the expected value of 30°. For Hypothesis 2, we calculated a one-way analysis of variance (ANOVA) to test the effects of light intensity on the perceived affordance boundary. For Hypothesis 3, we computed a 3 Light Intensity × 13 Angle repeated measures ANOVA to test the effects of light intensity on affordance judgement response time (RT). For Hypothesis 4, we employed separate repeated measures ANOVAs to test the effects of light intensity and slope angles on mean magnitude, CV, and ETC of COP sway and head sway. Mean magnitude and CV were included to act as control variables against measures of complexity. MFW was used as a dependent variable only for COP sway in a separate ANOVA. Finally, for Hypothesis 5, we followed up with mixed effects logistic regression models that attempted to predict affordance responses from head movements and COP sway.

Because postural sway is a nonstationary signal, classical measures of central tendency (e.g., mean magnitude, standard deviation) may not be the best way to describe the movements. Recently, Masoner et al. (2020) reported that ETC (Nagaraj & Balasubramanian, 2017a; 2017b) was a better predictor of affordance judgements compared to coefficient of variation and mean magnitude of head sway. Hajnal et al. (2022) solidified this point by showing that ETC is a better predictor than mean magnitude and coefficient of variation of perceptual responses in the affordance task of judging stand-on-ableness. Most recently, Peterson et al. (2024) have demonstrated that ETC is a significant predictor of learning about affordance of walking. Yet other studies using reachability as an affordance task (Doyon et al., 2020) have gotten similar results with MFW as the best predictor of perceptual performance.

ETC is especially well suited for the description of short time series (less than 500 samples). It is used in a variety of fields such as neuroscience, experimental psychology, and engineering. ETC measures the heterogeneity of the movement signal by identifying “streaks” (i.e. back-to-back identical or most similar values) in the time series. The “streaks” then get labeled as a single unit, which allows for a shortening of the time series. This labeling procedure repeats until the time series becomes a series of identical values, i.e. completely homogeneous. The process is similar to the one used in computer technology to compress electronic data files. The complexity of the time series depends on how many steps are required to shrink the length of the time series to its smallest possible length. Therefore, a high ETC value indicates large complexity, while a low ETC value indicates low complexity. At the same time, high complexity can be an indicator of increased exploratory activity, and thus promote perception of affordances. In the current study we computed ETC in two ways. ETC_{raw} is a simple count of the number of steps required to homogenize the time series. $ETC_{proportion}$ is defined as ETC_{raw}/N, where N is the length of the time series. $ETC_{proportion}$ was used to standardize the measurement due to the differences in response times.

Multifractal spectrum width was computed using the direct method (Chhabra & Jensen, 1989) in MATLAB. An accessible description of the conceptual algorithm is provided in a tutorial by Kelty-Stephen et al. (2013). The Euclidean time series is divided by n={1,…N) number of nonoverlapping bins. In each bin a linear regression fit is performed. At every given bin size, the residuals are summed to indicate the total amount of variability. The total variability is further weighted by exponent *q* which expresses the varying contributions of variability at different scales. The logarithm of the total weighted fluctuation function (which equals the sum of all weighted variability at different scales) is regressed against the logarithm of bin size. These slopes correspond to singularity strength (α) values. Next, the Shannon entropy of the fluctuation function is regressed against bin size in log-log plots. The slopes of those lines correspond to the Hausdorff dimension (*f*) values. The slope of the line of best fit at each chosen value of exponent q corresponds to the magnitude of change in variability across scales. Typically, $q<1$ values accentuate small measurements, whereas $q>1$ values accentuate large measurements. In the final step *f* is plotted as a function of α at each value of the *q* exponent. This typically creates an inverted U-shape curve. The multifractal spectrum width (MFW) is the difference between the maximal and minimal value of α. Larger spectrum width describes a signal with large heterogeneity (and thus exhibiting significant non-randomness). This quantity operationalizes the degree of complexity of the movement pattern.

We removed any outliers above 2.5 standard deviations of the mean response time, and any trials that did not record properly. All continuous sway parameters (mean magnitude, CV, ETC, MFW) were converted into z-scores for the purposes of the logistic regression analyses.

2.4 Procedure

After signing the consent form, participant's eye height was measured. Then the participant put on the VR headset display and was handed two controllers. Participants were instructed to stand still facing the VR tracking sensors with the controllers held down by their side.

The study consisted of 3 conditions (photopic, mesopic, and scotopic) each with 13 trials to test each slant angle. Each stimulus combination was repeated three times to provide for a reliable estimate of postural sway. Each participant was run through all three conditions. This resulted in a total of 13 angles × 3 lighting conditions × 3 repetitions = 117 trials per participant. The order of the conditions was counterbalanced. The lab was dark when the participants entered to allow for dark adaptation during the setup of the experiment.

During each trial a ramp was presented in the virtual environment and the participant was tasked with deciding whether they could stand upright with their feet flat on the ramp and their arms down to their side without bending at the knees or hip. The ramps were displayed in random order within each lighting condition and were presented from an egocentric point of view directly in front of the participant. While viewing the presented ramp, the participant was able to move their head freely while keeping the rest of the body still but was not allowed to walk inside the virtual environment. The participant used the controllers to record either a “yes” or “no” response and progress through the trials at their own pace. Specifically, the right-hand controller recorded the “yes” response and the left-hand controller recorded the “no” response. Response times were recorded for this task, beginning when the participant began each trial by pressing the left thumb stick, and ending when the participant made a judgement by pressing a button on a controller. After the participant completed the paradigm, they were debriefed on the purpose of the study.

CHAPTER III – RESULTS

3.1 Perceived Affordance Boundary

We conducted three one-sample t-tests to compare each lighting condition to the hypothetical value of 30 degrees. The perceived boundary was significantly smaller than 30 degrees in the scotopic ($M = 22.5^\circ$, 95% CI [19˚, 26˚]), $t(26) = 4.06$, $p < .001$, and mesopic condition ($M = 23.9^\circ$, 95% CI [21˚, 26.8˚]), $t(27) = 3.94$, $p < .001$, respectively. The photopic condition ($M = 28.5^\circ$, 95% CI [25.1˚, 31.9˚]) was not significantly different from 30 degrees ($p = .2$).

A one-way repeated measures analysis of variance (ANOVA) revealed a significant main effect of lighting condition on participants' affordance boundaries, $F(2, 52) = 12.65$, $p < .001$, $\eta_p^2 = .33$, indicating that perceptual judgements were affected by light intensity. The effect size suggests a moderate to large practical significance of the observed differences among lighting conditions. Pairwise comparisons were conducted using the method of Least Significant Difference (LSD). The photopic condition was significantly different from the mesopic ($p < .001$) and scotopic ($p < .001$) conditions. The mesopic condition was not significantly different from the scotopic condition ($p = .13$). Overall, there was a significant impact of lighting conditions on affordance perception, with the scotopic and mesopic conditions yielding the lowest affordance boundary. The results are depicted in *Figure 2*.

3.2 Response Time

A two-way repeated-measures ANOVA was conducted with lighting and slope as independent variables and response time as the dependent variable. There was no main effect of lighting on response time. However, there was a significant main effect of slope,

$F(4.76, 312) = 8.6$, $p < .001$, $\eta_p^2 = .25$. As shown in *Figure 3*, response time tended to be maximal near the perceived affordance boundaries and decreased for shallow and steep slopes. The interaction between slope and lighting conditions was statistically significant, $F(8.48, 624) = 2.4$, $p = .017$, $\eta_p^2 = .08$. Response times were longest around the corresponding affordance boundaries of each lighting condition. The longest average response time was 2.46 s for the 35° slope in the photopic condition, 2.21 s for the 25° slope in the mesopic condition, and 2.07 s for the 20° slope in the scotopic condition (see *Figure 3* for details).

3.3 Mean Magnitude and Variability of Head- and Postural Sway

We expected that mean magnitude and variability of head- and postural sway would be elevated under low lighting conditions indicative of less stability and an increased need for exploratory activity. This behavior could be exhibited by movements of a larger magnitude along more variable trajectories. Center of pressure (COP) recordings were converted into one dimensional time series by computing the frame-by-frame differences in displacement. The same procedure was done for computing the displacement time series of head sway. The mean magnitude was computed by taking the arithmetic average of the time series. The coefficient of variation (CV), defined as the ratio of standard deviation and the mean magnitude, served as a measure of variability.

Separate two-way ANOVAs with slope and lighting as independent variables were conducted on the mean magnitude and CV of COP. No main effects or interactions were statistically significant. The same analysis on mean magnitude of head sway also revealed no significant effects. However, the two-way ANOVA on coefficient of variation (CV) of head sway indicated a significant main effect of lighting condition,

$F(2,50)=527.2$, $p<.001$, $\eta_p^2=.96$. Post-hoc comparisons revealed that CV in the photopic condition was significantly smaller than in the mesopic and the scotopic conditions (LSD tests, $p<.001$; see *Figure 4* for details). Conspicuously, there were significant decreases in CV at the 20° and 25° in the mesopic and scotopic conditions, respectively.

3.4 Complexity of Head- and Postural Sway

First, we examined head movement complexity as analyzed by ETC. There were no significant effects of slope or lighting on ETC_{raw}. For $ETC_{proportion}$, the repeated measures ANOVA revealed no significant effect of lighting, although the effect of slope angle was significant, $F(4.26, 106.6) = 6.67$, $p < .001$, $\eta_p^2 = .21$, exhibited by smaller complexity near the affordance boundary, and higher complexity for shallow and steep angles. Furthermore, there was a significant interaction between lighting condition and slope, $F(11.5, 287.4) = 2.61$, $p < .003$, $\eta_p^2 = .1$. The results are shown in *Figure 5*. Complexity in all three lighting conditions exhibited a U-shaped pattern. Specifically, $ETC_{proportion}$(head) was minimal near the affordance boundary increasing as the slope angle got shallower and steeper, respectively. Examination of the minimum values revealed that the photopic condition had the lowest $ETC_{proportion}$(head) value at 35°, the mesopic at 25°, and the scotopic condition at 20°, around each lighting condition's corresponding affordance boundary.

Next, we examined postural sway complexity based on COP. Thanks to the high sampling rate of the COP signal, it was possible to calculate the multifractal spectrum width (MFW), in addition to the $ETC_{proportion}$ for COP. The repeated measures ANOVA on $ETC_{proportion}$(COP) revealed no significant main effects or interactions. The same ANOVA conducted on MFW(COP) returned a significant main effect of slope angle,

$F(7.2, 165.7) = 2.74$, $p < .009$, $\eta_p^2 = .11$. Post hoc comparisons using Bonferroni correction revealed that MFW(COP) at 30° was significantly smaller than at 10°. The results (shown in *Figure 6*) exhibited a U-shaped pattern across slope angles, similar to the pattern observed for $ETC_{proportion}$(head).

3.5 Does Complexity of Exploratory Activity Predict Affordance Perception?

Hypothesis 5 was set up to test if perception can be predicted by an interaction of lighting conditions and complexity of body movements. Following numerous recent empirical investigations (e.g. Doyon et al., 2020; Hajnal et al., 2018; 2022) and theoretical considerations about the necessity of exploration for affordance perception (Hajnal, 2024) we conjectured that perception should be determined by an interaction of experimental design variables with the effects of exploratory activity. Specifically, we hypothesized that the best predictor of affordance perception should be the complexity of exploration.

Since affordance judgments were measured with a dichotomous variable (yes/no), and because our data had a nested structure (i.e. trials nested within repetitions, nested within lighting conditions, nested within subjects, etc.), we used a mixed-effects hierarchical logistic regression (*lmer* statistical package in R; see Bates et al., 2014) as it is a more appropriate analysis than ANOVA for this type of data. The following model was used:

Perception ~ Trial + MEAN×Slope×Lighting + CV×Slope×Lighting +

Complexity×Slope×Lighting + (Trial|Participant).

Trial and Participant were set as random effects; all other variables were fixed effects. Lighting was coded as a categorical variable with three levels: 1= scotopic (control), 2= mesopic, 3= photopic. The main effects of Lighting and interactions involving the lighting variable were based on the comparison with the baseline lighting level (scotopic illumination). Two separate models were considered – one based on head sway, and the other based on center of pressure (COP).

Modeling proceeded by adding MEAN×Slope×Lighting to the null model first, CV×Slope×Lighting second, and Complexity×Slope×Lighting last. MEAN and CV of head sway and COP sway, respectively, were not significant predictors nor did they significantly interact with design variables in any of the models. Consequently, these predictors were excluded from further regression models. *Tables 1-5* list the results of the various regression models. To streamline the presentation of results for the various models and to evaluate the conjectures of Hypothesis 5, we will highlight only those significant effects in which the complexity measure significantly interacted with the various lighting conditions.

3.5.1 Complexity of Head Sway as a Predictor of Affordance Perception

3.5.1.1 Effects of ETC_{raw} based on Head Sway

There was a significant positive ETC_{raw}×$Lighting_{photo\text{-}scoto}$ interaction (β=1.509, *SE*= 0.565, *p*=.008, *OR*=4.521), suggesting that the difference in perception between the photopic and scotopic condition increased as complexity increased. This effect was further qualified by a negative ETC_{raw}×$Lighting_{photo\text{-}scoto}$×Angle interaction ($\beta$=-0.056, *SE*= 0.018, *p*=.002, *OR*=0.946), such that at larger angles the difference between photopic and scotopic conditions brought about by increases in ETC was diminished. *Table 1* shows the output of the statistical analyses.

3.5.1.2 Effects of $ETC_{proportion}$ based on Head Sway

There were no significant effects of $ETC_{proportion}$ or interactions with Lighting. *Table 2* shows the output of the statistical analyses.

3.5.2 Complexity of Center of Pressure Sway as a Predictor of Affordance Perception

3.5.2.1 Effects of ETC_{raw} based on Center of Pressure Sway

There was a significant negative ETC_{raw}×Angle×$Lighting_{meso\text{-}scoto}$ interaction (β=-0.068, *SE*= 0.034, p=.045, *OR*=0.934). As ETC_{raw} increased, participants transitioned from perceiving the ramp as stand-on-able to not stand-on-able at ever steeper slopes. This tendency was significantly more pronounced in the mesopic compared to the scotopic condition. *Table 3* shows the output of the statistical analyses.

3.5.2.2 Effects of $ETC_{proportion}$ based on Center of Pressure Sway

The main effect of $ETC_{proportion}$ was significant (β=-0.914, *SE*= 0.252, p<.001, *OR*=0.401), meaning that an increase in ETC resulted in decreased likelihood of saying 'yes' as to the stand-on-ability of ramps. This effect was qualified by a positive $ETC_{proportion}$×Angle interaction (β=0.028, *SE*= 0.005, p<.001, *OR*=1.028), such that with increasing angles the increase in $ETC_{proportion}$ made the drop in likelihood of saying 'yes' less pronounced. In other words, increased $ETC_{proportion}$ had the most impact on perception at smaller angles. Importantly, $ETC_{proportion}$ did not significantly interact with Lighting. *Table 4* shows the output of the statistical analyses.

3.5.2.3 Effects of MFW based on Center of Pressure Sway.

There was no significant main effect of MFW, however, the MFW×$Lighting_{photo\text{-}scoto}$ interaction was significant (β=-1.975, *SE*= 0.838, p=.018, *OR*=0.139). This meant that the difference in perception between trials with large and small MFW was larger under photopic lighting compared to under scotopic lighting. Specifically, trials with smaller MFW of sway resulted in more ‘yes’ responses compared to trials with larger MFW under photopic lighting. This pattern was reversed under scotopic lighting. The significant positive MFW×$\text{Lighting}_{\text{photo-scoto}}$×Angle interaction ($\beta$=0.085, *SE*= 0.033, *p*=.011, *OR*=1.089) accentuated this effect as slope angles increased. *Table 5* shows the output of the statistical analyses.

CHAPTER IV – DISCUSSION

The purpose of the current study was to see how lighting conditions influence affordance perception (Hypotheses 1 & 2), response time (Hypothesis 3), and movement complexity (Hypothesis 4), and if the interaction of light intensity and movement complexity predicts affordance judgements (Hypothesis 5). The overall motivation for the hypotheses was that less light should lead to diminished perception, as measured by affordance boundaries, response time, and movement complexity. Specifically, less light should provide less opportunities to detect information, so the perception-action system would need to explore more to detect the relevant information that determines the affordance. This exploration is typically manifested through complex exploratory activity that samples ambient energy.

4.1 The Effect of Ambient Light on Affordance Perception

The results indicated that the perceived affordance boundary was less than 30 degrees in both the scotopic and mesopic conditions, supporting Hypothesis 1. Participants were less likely to say “yes” to the stand-on-ability of a ramp under low lighting relative to the same ramp in the brighter conditions. If we assume the low lighting conditions permit the detection of visual information of diminished quality, we would expect participants to be more conservative with their judgements in low light, i.e. shallow angles would be perceived as steeper, and thus less likely to afford safe upright stance. In real world scenarios, this could help to decrease potential risk caused from misperceiving, such as tripping or falling. Future studies should test this paradigm in a real-world environment to see if the effect remains. Because our study design did not manipulate participant’s stance, it is possible that the smaller affordance boundaries we measured in the lower lighting conditions (mesopic and scotopic) could be the result of postural sway changes as the light decreases.

Hypothesis 2 predicted that the affordance boundary would be lowest in low light and increase relative to the lighting conditions. Our results supported this prediction, with scotopic (22.5˚) having the lowest affordance boundary followed by mesopic (23.9˚) and photopic (28.5˚) light. Under brighter lighting conditions the perceived affordance boundary for stand-on-ability increased relative to the mesopic and scotopic conditions, meaning observers perceived they can stand on steeper slopes. Even though we did not measure the activity of the photoreceptors during the experimental trials, it is possible that optimal detection of information for affordances requires both adequate visual acuity provided by cones and enhanced sensitivity provided by rods. Future neurological studies could supply the evidence for this hypothesis by investigating which visual receptors are active under different lighting conditions. We found that there was a significant difference between the photopic condition and the mesopic and scotopic conditions, but that the mesopic and scotopic conditions did not differ significantly. This is likely because of the much larger difference between the measured lux levels in the photopic (440 lx) condition compared to the mesopic (3 lx) and scotopic (1 lx) condition. Mesopic lighting contains a wide range of lighting conditions (1 lx – 50 lx), so perhaps a brighter mesopic condition would have yielded no difference between photopic and mesopic lighting conditions. In addition, it is important to note that the transition between scotopic, mesopic, and photopic vision is gradual and varies among individuals. Factors such as age, eye health, and adaptation to low light can influence an individual's perception in mesopic conditions.

4.2 The Effect of Ambient Light on Response Time

We predicted that due to diminished affordance detection, participants would take longer to make a decision under low lighting conditions (Hypothesis 3). However, the data analysis showed that there was no main effect of lighting on response time. This means that response time did not differ between lighting conditions. There was a significant interaction between lighting and slope, such that response time was longest around each lighting condition's respective affordance boundary, increasing from darkest to brightest. This was expected, as previous literature (Doyon et al., 2019; Hajnal et al., 2022; Masoner et al., 2020) has repeatedly shown that response time tends to be longest at the affordance boundary, and this effect seems to translate to other lighting conditions that have lower affordance boundaries. Early research on affordances of stand-on-ability has demonstrated that latencies tend to increase around affordance boundaries (Fitzpatrick et al., 1994). This result is consistent with the conception of perception-action systems as self-organized dynamical systems (Kelso, 1995). One of the characteristic features of dynamical systems is that they exhibit critical fluctuations around behavioral transition points, such as between perceiving a slope to afford or not afford standing upright. Critical fluctuations have been associated with increased latencies around those transition points (known as affordance boundaries in affordance research). Numerous empirical investigations of affordances have demonstrated this effect (Doyon et al., 2019; Hirose & Nishio, 2001; Lopresti-Goodman et al., 2009; Richardson et al., 2007; van der Kamp et al., 1998).

Participants kept the same pace of responding regardless of lighting conditions. Even though they were more conservative in their judgements under dimmer light, on average they took the same amount of time to respond. Perhaps this is due to the study taking place in a virtual environment, with no real sense of consequences if the judgement was a mistake. It is worth noting again that participants only made judgements, never attempted to step onto a real ramp surface, nor did they receive any visual or haptic feedback about accuracy. This could have contributed to low participant motivation. Perhaps a real-world environment with feedback would produce longer response times and reveal sensitivity to lighting, due to the addition of behavioral consequences. For instance, participants may not be as confident in their judgements in a real world setting and would be more likely to take longer to make the decision if there were a threat of injury due to falling.

4.3 The Effect of Ambient Light on Head Movement Complexity When Measured by Effort to Compress (ETC)

Hypothesis 4 predicted that complexity of head movements, not measures of central tendency and variability such as mean magnitude or coefficient of variation, should be the highest in the scotopic condition when compared to the mesopic or photopic conditions because we expected exploratory movements to increase under less light. While there was no significant effect of angle or lighting on the mean magnitude of head sway, there was an effect of lighting on CV, indicating that head movements were less varied in the photopic condition, compared to mesopic and scotopic. It seems like exploratory activity was more varied when the circumstances of information detection were not optimal (i.e. under low light). Since the information is a complex pattern of ambient optic and kinesthetic flow it is quite possible that exploratory activity could have been used in at least two ways: 1) participants may have chosen to move in complex ways to “unlock” and match the complexity of the informational pattern (see Stephen et al., 2008; West et al., 2008 for a related hypothesis about *complexity matching* between perception-action systems); and 2) participants may have chosen to move in complex ways under dim lighting to get more varied samples of the optic flow pattern than otherwise. It is unclear if these tendencies are simply additive or not. If additive, then the expectation would be that participants would move in the most complex ways under dim lighting, compounding the requirements of information detection due to the nature of information and the vagaries of environmental lighting conditions. Future studies are planned to explicitly and independently control the availability of information, and the amount and type of exploratory activity in affordance tasks.

We hypothesized that in low light the perceiver would increase their movement complexity to reveal more salient visual information from more perspectives of the optic array to guide their affordance responses. Results revealed that there was a significant interaction between light and slope angle, such that $ETC_{proportion}$ was lowest around the affordance boundaries for each lighting condition (see *Figure 5*). This indicated that the perceiver’s movements became less complex when the task was difficult (near the perceived affordance boundary). The prediction about task difficulty is corroborated by the results of past research on the affordance of stand-on-ability. Participants tend to be less certain about the accuracy of their perception around the perceived affordance boundary, demonstrating that the task gets difficult (Doyon et al., 2019; Fitzpatrick et al., 1994). A decrease in complexity at the transition point was expected based on previous literature (Hajnal et al., 2022), which showed that head movement complexity was lowest at the affordance boundaries of stand-on-ability. The interaction between lighting conditions and slope angle revealed that perceptual judgements of stand-on-ability ordinally matched the minima of $ETC_{proportion}$ as well as the maxima of response times as light intensity and surface angle changed. In summary, head movements are significantly related to the interaction of light and slope angle, such that complexity of head movements was lowest around each lighting condition's affordance boundaries. The ordinal correspondence of perceived affordance boundaries, peak response times and complexity minima point to a yet-to-be-discovered underlying information pattern, subject to future research.

4.4 The Effect of Ambient Light on Center of Pressure (COP) When Measured by Effort to Compress (ETC) and Multifractal Spectrum Width (MFW)

One of the hallmark features of dynamical systems is their highly integrated nature. Measurements at any relevant part of the system should reveal perceptual and action capabilities in equivalent ways. This feature is oftentimes referred to as functional specificity – the tendency of the whole system to put itself in the service of a common behavioral goal, i.e. perceive and act out an affordance irrespective of the particular anatomical parts that are involved (Hajnal et al., 2016; Surber et al., 2022; Wagman & Hajnal, 2014; 2016). As a consequence, Hypothesis 4 also served as an implicit test of functional specificity: by taking measurements of exploratory activity from the head and from under the feet related to the movement complexity of postural sway, as measured by center of pressure (COP). Traditionally, movement complexity has been measured by COP, usually with participants standing on a force plate. With the emergence of virtual reality technology in perception research, movement complexity has begun to be measured from the head, due to the VR headset being able to track movements in 3D space. To our knowledge so far, no studies have measured movement complexity from both the head and feet.

There were no significant effects on complexity of COP sway when measured with $ETC_{proportion}$. When we examined the Multifractal Spectrum Width (MFW) of the COP trajectories, we found no significant effect of lighting. However, we did find that MFW was lowest for the 30-degree slopes (see *Figure 6*), which corresponds to the average affordance boundary for stand-on-ability under full lighting in young adults.

It appears that the MFW of COP and $ETC_{proportion}$ of head movements are minimal at the affordance boundary (see *Figure 5* and *6*). Interestingly, the effects of lighting and angle on $ETC_{proportion}$ of COP were not significant like for head movements. It is important to note that head sway has a larger degrees of freedom compared to measuring COP from a force plate. Head movements take place in three dimensions, whereas COP is a two-dimensional representation of postural sway projected onto the X-Y coordinate system of the force plate device. The human head is sitting atop an elongated body and neck that is far from the ground when standing. Many subtle postural adjustments are continuously needed to prevent toppling over, whereas the feet press firmly against the ground, where the flat soles of your feet distribute your mass more evenly. A second, more methodological problem was that the virtual reality headset recorded at a much lower sampling rate than the COP force plate. Because ETC is better suited for shorter time series, it follows why we may have seen a significant effect of ETC for head movements but not for COP.

To summarize the results of Hypothesis 4, we measured participants' postural sway from the head (using mean magnitude, CV, & ETC) and feet (using mean magnitude, CV, ETC, and MFW). Complexity measures exhibited significant effects and interactions, whereas mean magnitude and CV did not (with the exception of the effect of light on CV of head sway). For head sway, $ETC_{proportion}$ was lowest at each lighting condition's affordance boundary. MFW showed similar pattern of results, but without the influence of lighting conditions. This general correspondence should give researchers confidence that measuring complexity from different anatomical parts and using different computational algorithms (MFW and ETC) may provide solid evidence that the perception-action system (conceived as a dynamical system) exhibits functional specificity in affordance tasks.

4.5 The Predictive Power of Exploratory Activity Lies in Complexity

In the preceding analyses parameters describing head- and postural sway were used as dependent variables in ANOVAs and t-tests. The input for these statistical methods were average values computed over repetitions of trials. Thus, lots of variance was lost that may have weakened statistical power. Furthermore, using these parameters as outcome variables does not represent the direction of causality of the perceptual process appropriately. It is more realistic to treat perception as the outcome variable that is shaped by the influence of experimental design variables and parameters of exploratory activity. Due to these reasons Hypothesis 5 was designed to test whether perceptual judgements could be predicted by the movement parameters' interaction with task design factors. Hierarchical mixed effects logistic regression analyses are best suited for evaluating this hypothesis because 1) they have fewer statistical assumptions about distributions and variance, and 2) researchers can work directly with raw data and account for trial-by-trial variability more judiciously than ANOVAs.

Based on the results of Hypothesis 5, the measures of central tendency (mean magnitude and CV) obtained from head- and postural sway were not significant predictors of affordance responses. This was expected based on the implicit prediction of Hypothesis 5 that the complexity of information patterns (optic flow) should be best matched by the complexity of exploratory activity brought about by head- and postural sway. ETC_{raw} significantly interacted with lighting both via head sway (see *Table 1*) and through postural (COP) sway (see *Table 3*) to serve as a significant predictor of perceptual responses. The same was true of MFW based on postural sway (see *Table 5*).

The lack of significant interaction with parameters that assume stationarity, such as mean magnitude and CV, indicates that it is the complexity of movements that is important for predicting affordance responses, and not how large or varied the movements are. We suspect that participants were using these subtle body movements to inform their perception of stand-on-ability of presented surfaces. It is still an open question whether observers spontaneously self-selected more complex exploratory movements because 1) they provided better opportunities for detecting the information that specifies affordance perception, or because 2) they needed to select complex movements under varying ambient light to increase the variety of sampling opportunities of said energy arrays. Follow up studies are planned to tease apart the potential influence of these two possibilities.

4.6 The Correspondence between ETC and MFW as Measures of Complexity

The current study was not set up to evaluate which complexity measure was a better predictor of perception. MFW measures complexity of movements across multiple temporal and spatial scales, whereas ETC is simpler and does not explicitly quantify interactions across multiple scales of the dynamical system. The ETC algorithm used in the current paper has a low threshold for finding "pockets of homogeneity" in the time series, because the criteria for compression requires only two neighboring points to be identical (or most similar among all possible pairs) to "merge" them into a single unit. Furthermore, each iteration of the algorithm checks the whole time series, whereas MFW is computed by binning the time series at different scales and computing regression fits local to each bin size. One strategy to account for multiscale interactions would be to use the binning method for ETC, and to increase the criteria for what counts as a streak in the time series from two consecutive data points to three or more. Another finding in the current dataset was the fact that ETC_{raw} and response time were positively correlated. One way to test if the effects of ETC are independent of response time is to provide a fixed amount of time for exploration on each trial (e.g. 5 seconds) in future studies. If the effects of lighting persist when exploration time is fixed, then we could be more certain that ETC has a unique contribution to predict affordance perception independent of response latency.

The ecological approach to perception and action assumes that information maps onto perception in a 1:1 fashion (Michaels & Beek, 1995). The regression models were set up to provide circumstantial evidence that such an informational pattern exists. While the exact nature of the information pattern remains unknown, these models strongly suggest that complexity of exploratory activity must be a key component of this pattern. A growing list of empirical investigations has provided evidence that nonlocomotor body movements during trials play a key role in predicting perception in a variety of affordance tasks (Hajnal et al., 2018; Hajnal et al., 2022; Masoner et al., 2020). The current study showed that there is a relationship between postural sway complexity, whether measured from the head or feet, and affordances. Specifically, we showed that perception of stand-on-ability under different lighting conditions can be predicted using MFW and ETC from COP, and ETC from the head.

4.7 Limitations and Future Directions

This study was aimed at studying perception within a virtual reality environment. Previous literature has shown significant differences in perception and behavior in virtual and real environments (Banerjee et al., 2021; Feldstein et al., 2020). In the context of the current study there is the issue of measuring physical light output at the eye from the VR lenses. Boon et al. (2021) developed a method to estimate Unity Engine Candelas into real world lux units, measured 12 mm from the lenses of the Oculus Quest. However, there needs to be more replications to test the reliability of the measured illuminance. Importantly, replications should compare the results obtained in virtual reality to a real-world paradigm.

Through the discussion of Hypothesis 1, it became apparent that the smaller affordance boundary in the scotopic condition could be caused either from less light or a change in postural sway. It is quite plausible that observers in the dark spontaneously increase their degrees of freedom of movements to increase exploratory activity. One important aspect of future testing needs to be careful control and manipulation of posture. Quiet stance has to be compared to postures where exploratory activity is limited, such as when one leans back against a wall while standing, or when touching a rigid surface, such as a wall, with their hand (the “light touch paradigm”, Jeka, 1997). We plan to follow up with another study to investigate how these stance differences are influenced by lighting condition. The purpose of these studies is to further tease apart the relationship between ambient light and postural sway in the service of affordance perception.

The current study investigated the stand-on-ability of an angled surface, but researchers should test how ambient light intensity affects other affordances of daily living, such as reachability or graspability. Finally, future research should determine whether ETC or MFW is a better predictor of affordance responses.

4.8 Conclusion

To summarize, we found that (1) affordance judgements under scotopic and mesopic light were more conservative than under photopic light, (2) response times were longest around slope angles that corresponded to affordance boundaries of each lighting condition, (4) complexity measurements of head- and postural sway significantly interacted with light and angle compared to mean magnitude and CV, and were at their lowest level at the affordance boundaries. Finally, (5) affordance responses were best predicted by complexity measures of exploratory activity. The general conclusion supports a view of perception as an active process in service of guiding functionally relevant behaviors. There are numerous possible implications of the results of this study, such as for evaluating fall risk in impacted populations (i.e. elderly). These results indicate that there is need to design safe areas of daily living with sufficient lighting, specifically areas with sloped walkways to prevent falling.

APPENDIX A – TABLES

Table A1. *Mixed Effects Logistic Regression Model of Affordance Judgments Using ETCraw(head) as a Predictor*

Predictor	*β*	*SE*	*p*	*odds ratio*	*lower 95% CI*	*upper 95% CI*
Intercept	**8.389**	**0.927**	**<0.001**	**4398.449**	**715.504**	**27038.800**
Trial	**-0.013**	**0.006**	**0.027**	**0.987**	**0.975**	**0.998**
ETC	**-1.331**	**0.364**	**<0.001**	**0.264**	**0.129**	**0.539**
Lighting$_{meso-scoto}$	**3.962**	**0.870**	**<0.001**	**52.543**	**9.552**	**289.016**
Lighting$_{photo-scoto}$	**3.764**	**0.859**	**<0.001**	**43.115**	**8.004**	**232.249**
Angle	**-0.368**	**0.026**	**<0.001**	**0.692**	**0.659**	**0.728**
ETC×Lighting$_{meso-scoto}$	0.623	0.706	0.378	1.864	0.467	7.431
ETC×Lighting$_{photo-scoto}$	**1.509**	**0.565**	**0.008**	**4.521**	**1.494**	**13.680**
ETC×Angle	**0.046**	**0.011**	**<0.001**	**1.047**	**1.025**	**1.070**
Angle×Lighting$_{meso-scoto}$	**-0.106**	**0.033**	**0.001**	**0.900**	**0.843**	**0.960**
Angle×Lighting$_{photo-scoto}$	-0.026	0.030	0.387	0.975	0.920	1.033
ETC×Angle×Lighting$_{meso-scoto}$	-0.032	0.027	0.238	0.969	0.919	1.021
ETC×Angle×Lighting$_{photo-scoto}$	**-0.056**	**0.018**	**0.002**	**0.946**	**0.912**	**0.980**

Note: Results are based on this model: Perception = Trial + ETC×Lighting×Angle + (Trial|Subject). The subscripts for the Lighting variable indicate which two conditions are part of the comparison. The odds ratio and the confidence intervals serve as estimates of effect size. ETC values were converted to z scores. Statistically significant effects ($p<0.05$) are printed in bold font.

Table A2. *Mixed Effects Logistic Regression Model of Affordance Judgments Using $ETC_{proportion}$(head) as a Predictor*

Predictor	β	*SE*	*p*	*odds ratio*	*lower 95% CI*	*upper 95% CI*
Intercept	**8.048**	**0.923**	**<0.001**	**3128.818**	**512.108**	**19116.090**
Trial	**-0.013**	**0.006**	**0.025**	**0.987**	**0.975**	**0.998**
ETC	0.185	0.419	0.658	1.204	0.530	2.735
$Lighting_{meso\text{-}scoto}$	**4.681**	**0.908**	**<0.001**	**107.831**	**18.203**	**638.772**
$Lighting_{photo\text{-}scoto}$	**4.270**	**0.852**	**<0.001**	**71.526**	**13.454**	**380.272**
Angle	**-0.354**	**0.025**	**<0.001**	**0.702**	**0.668**	**0.736**
ETC×$Lighting_{meso\text{-}scoto}$	0.755	0.786	0.337	2.127	0.455	9.935
ETC×$Lighting_{photo\text{-}scoto}$	-0.831	0.627	0.186	0.436	0.127	1.490
ETC×Angle	-0.007	0.018	0.706	0.993	0.960	1.028
Angle×$Lighting_{meso\text{-}scoto}$	**-0.136**	**0.035**	**<0.001**	**0.873**	**0.815**	**0.935**
Angle×$Lighting_{photo\text{-}scoto}$	-0.042	0.029	0.148	0.959	0.906	1.015
ETC×Angle×$Lighting_{meso\text{-}scoto}$	-0.028	0.031	0.367	0.973	0.916	1.033
ETC×Angle×$Lighting_{photo\text{-}scoto}$	0.042	0.023	0.070	1.043	0.997	1.092

Note: Results are based on this model: Perception = Trial + ETC×Lighting×Angle + (Trial|Subject). The odds ratio and the confidence intervals serve as estimates of effect size. ETC values were converted to z scores. Statistically significant effects ($p<0.05$) are printed in bold font.

Table A3. *Mixed Effects Logistic Regression Model of Affordance Judgments Using ETC_{raw}(COP) as a Predictor*

Predictor	*β*	*SE*	*p*	*odds ratio*	*lower 95% CI*	*upper 95% CI*
Intercept	**9.72**	**1.06**	**<0.001**	**16647.61**	**2094.536**	**132317.2**
Trial	**-0.02**	**0.01**	**0.002**	**0.980**	**0.968**	**0.993**
ETC	**-1.09**	**0.36**	**0.002**	**0.338**	**0.168**	**0.677**
$Lighting_{meso-scoto}$	**4.4**	**0.96**	**<0.001**	**81.441**	**12.5**	**530.606**
$Lighting_{photo-scoto}$	**5.279**	**1.07**	**<0.001**	**196.225**	**23.955**	**1607.351**
Angle	**-0.4**	**0.03**	**<0.001**	**0.669**	**0.632**	**0.709**
ETC×$Lighting_{meso-scoto}$	1.448	0.83	0.082	4.255	0.834	21.701
ETC×$Lighting_{photo-scoto}$	0.826	0.66	0.213	2.283	0.623	8.371
ETC×Angle	**0.042**	**0.01**	**0.001**	**1.042**	**1.017**	**1.069**
Angle×$Lighting_{meso-scoto}$	**-0.11**	**0.04**	**0.004**	**0.900**	**0.838**	**0.967**
Angle×$Lighting_{photo-scoto}$	**-0.073**	**0.037**	**0.049**	**0.929**	**0.864**	**1.000**
ETC×Angle×$Lighting_{meso-scoto}$	**-0.068**	**0.034**	**0.0454**	**0.934**	**0.874**	**0.999**
ETC×Angle×$Lighting_{photo-scoto}$	-0.03	0.023	0.1907	0.970	0.928	1.015

Note: Results are based on this model: Perception = Trial + ETC×Lighting×Angle + (Trial|Subject). The odds ratio and the confidence intervals serve as estimates of effect size. ETC values were converted to z scores. Statistically significant effects ($p<0.05$) are printed in bold font.

Table A4. *Mixed Effects Logistic Regression Model of Affordance Judgments Using $ETC_{proportion}$(COP) as a Predictor*

Predictor	*β*	*SE*	*p*	*odds ratio*	*lower 95% CI*	*upper 95% CI*
Intercept	**9.666**	**1.067**	**<0.001**	**15767.81**	**1946.835**	**127706.6**
Trial	**-0.021**	**0.006**	**<0.001**	**0.979**	**0.967**	**0.992**
ETC	**-0.914**	**0.252**	**<0.001**	**0.401**	**0.244**	**0.657**
$Lighting_{meso-scoto}$	**4.595**	**0.958**	**<0.001**	**98.997**	**15.132**	**647.688**
$Lighting_{photo-scoto}$	**5.514**	**1.064**	**<0.001**	**248.046**	**30.825**	**1996.025**
Angle	**-0.396**	**0.028**	**<0.001**	**0.673**	**0.637**	**0.712**
ETC×$Lighting_{meso-scoto}$	1.632	0.962	0.090	5.114	0.776	33.680
ETC×$Lighting_{photo-scoto}$	0.591	0.874	0.499	1.806	0.326	10.007
ETC×Angle	**0.028**	**0.005**	**<0.001**	**1.028**	**1.018**	**1.038**
Angle×$Lighting_{meso-scoto}$	**-0.115**	**0.036**	**0.002**	**0.891**	**0.830**	**0.957**
Angle×$Lighting_{photo-scoto}$	**-0.082**	**0.036**	**0.024**	**0.921**	**0.858**	**0.989**
ETC×Angle×$Lighting_{meso-scoto}$	-0.071	0.039	0.073	0.932	0.862	1.007
ETC×Angle×$Lighting_{photo-scoto}$	-0.015	0.029	0.607	0.985	0.931	1.042

Note: Results are based on this model: Perception = Trial + ETC×Lighting×Angle + (Trial|Subject). The odds ratio and the confidence intervals serve as estimates of effect size. ETC values were converted to z scores. Statistically significant effects ($p<0.05$) are printed in bold font.

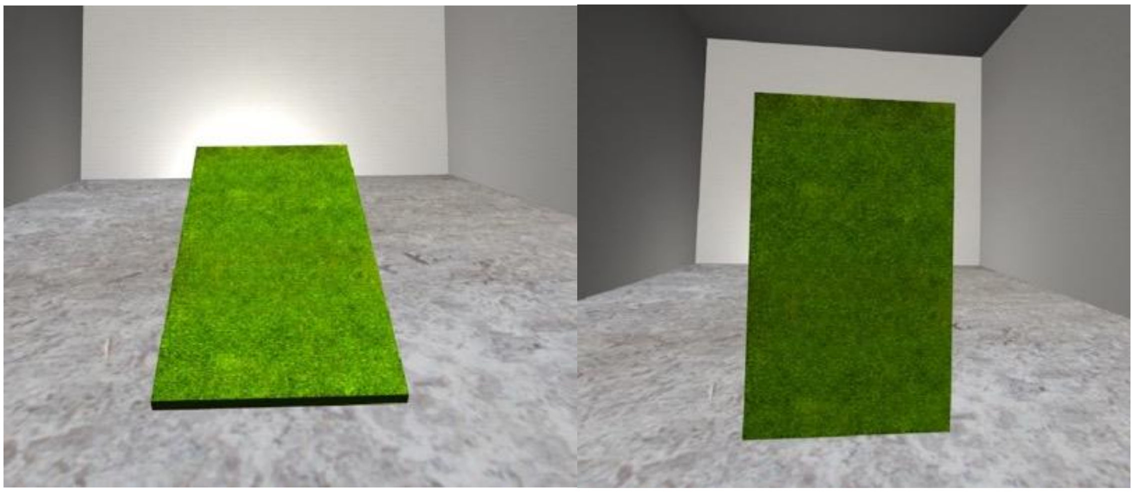
Table A5. *Mixed Effects Logistic Regression Model of Affordance Judgments Using MFW(COP) as a Predictor*

Predictor	*β*	*SE*	*p*	*odds ratio*	*lower 95% CI*	*upper 95% CI*
Intercept	**9.916**	**1.071**	**<0.001**	**20261.26**	**2481.405**	**165438**
Trial	**-0.021**	**0.006**	**0.001**	**0.979**	**0.967**	**0.992**
MFW	1.130	0.683	0.098	3.095	0.811	11.807
Lighting$_{meso\text{-}scoto}$	**3.948**	**0.941**	**<0.001**	**51.821**	**8.201**	**327.436**
Lighting$_{photo\text{-}scoto}$	**5.145**	**1.055**	**<0.001**	**171.508**	**21.698**	**1355.66**
Angle	**-0.410**	**0.030**	**<0.001**	**0.664**	**0.626**	**0.704**
MFW×Lighting$_{meso\text{-}scoto}$	-0.948	1.096	0.387	0.388	0.045	3.319
MFW×Lighting$_{photo\text{-}scoto}$	**-1.975**	**0.838**	**0.018**	**0.139**	**0.027**	**0.717**
MFW×Angle	**-0.058**	**0.029**	**0.042**	**0.943**	**0.892**	**0.998**
Angle×Lighting$_{meso\text{-}scoto}$	**-0.080**	**0.036**	**0.027**	**0.923**	**0.860**	**0.991**
Angle×Lighting$_{photo\text{-}scoto}$	-0.063	0.037	0.086	0.939	0.874	1.009
MFW×Angle×Lighting$_{meso\text{-}scoto}$	0.069	0.044	0.113	1.072	0.984	1.167
MFW×Angle×Lighting$_{photo\text{-}scoto}$	**0.085**	**0.033**	**0.011**	**1.089**	**1.020**	**1.163**

Note: Results are based on this model: Perception = Trial + MFW×Lighting×Angle + (Trial|Subject). The odds ratio and the confidence intervals serve as estimates of effect size. MFW values were converted to z scores. Statistically significant effects ($p<0.05$) are printed in bold font.

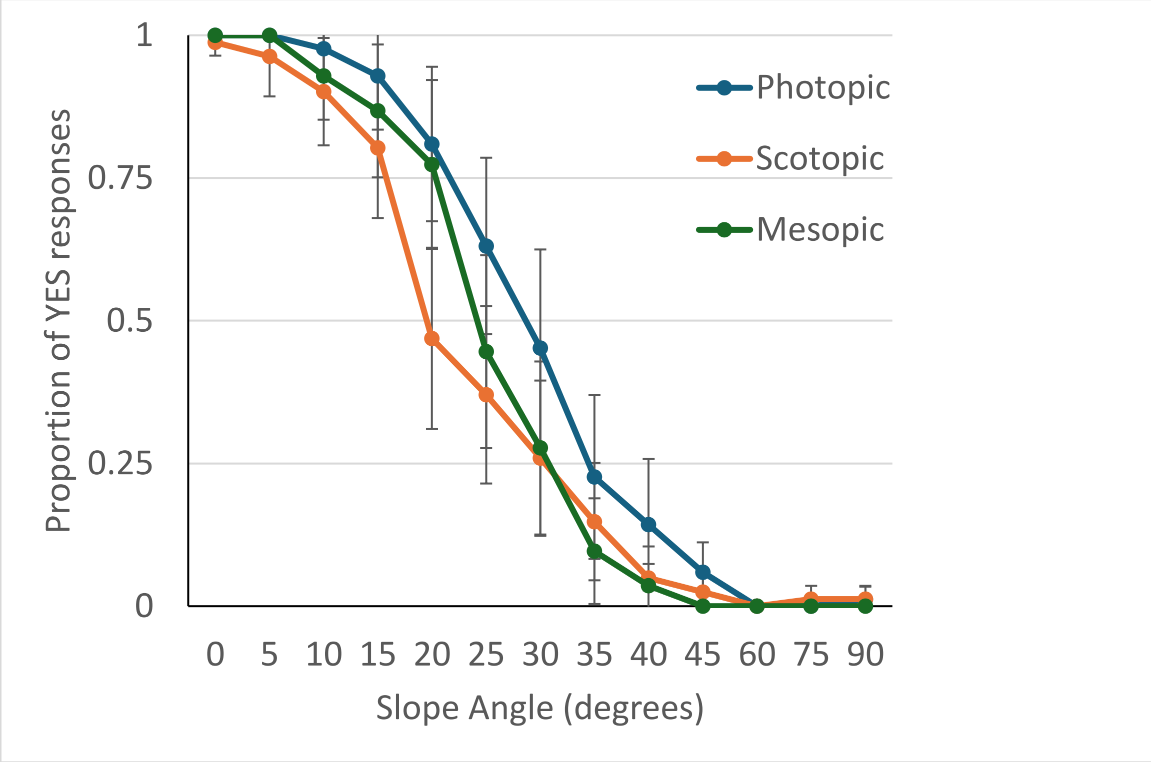
APPENDIX B – FIGURES

Figure A1. *Examples Of Stimulus Trials for a 45° And 90° Ramp from the Viewpoint of the Observer in the VR*



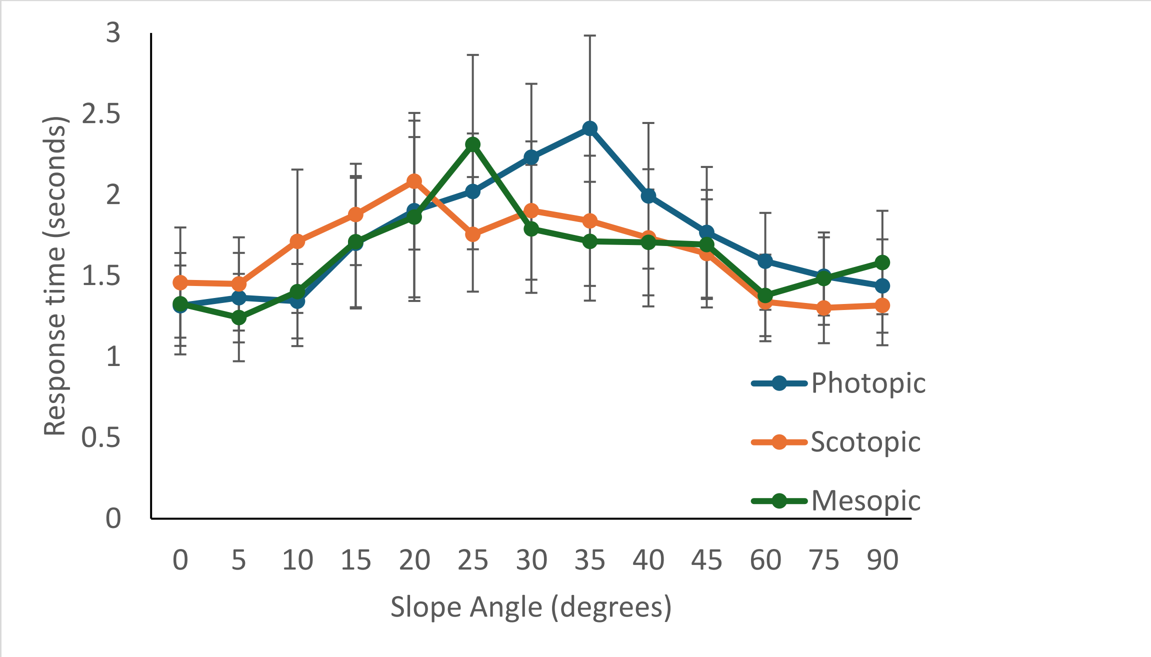
Note: In the experiment the participant stood one meter in front of the base of the ramp, so the ramp surface would occupy progressively larger portions of the visual field for steeper slopes.

Figure A2. *Affordance Judgments (Average Proportion of YES Responses) as a Function of Slope Angles and Lighting Conditions*



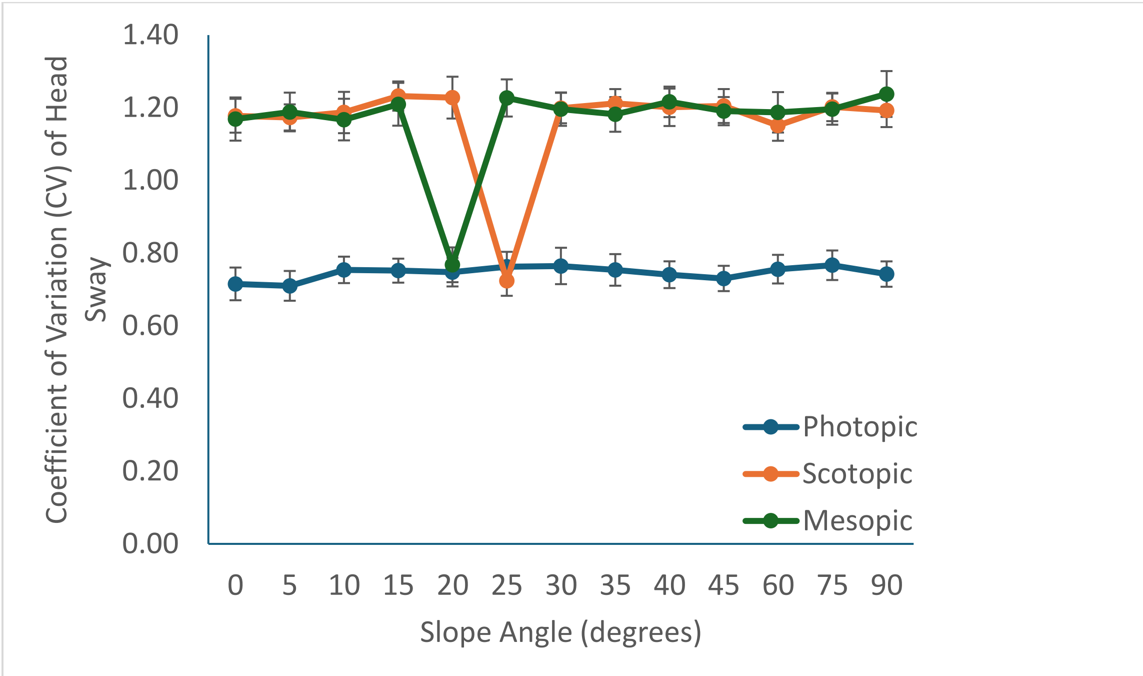
Note: The error bars represent 95% confidence intervals.

Figure A3. *Response Time as a Function of Slope Angles and Lighting Conditions*



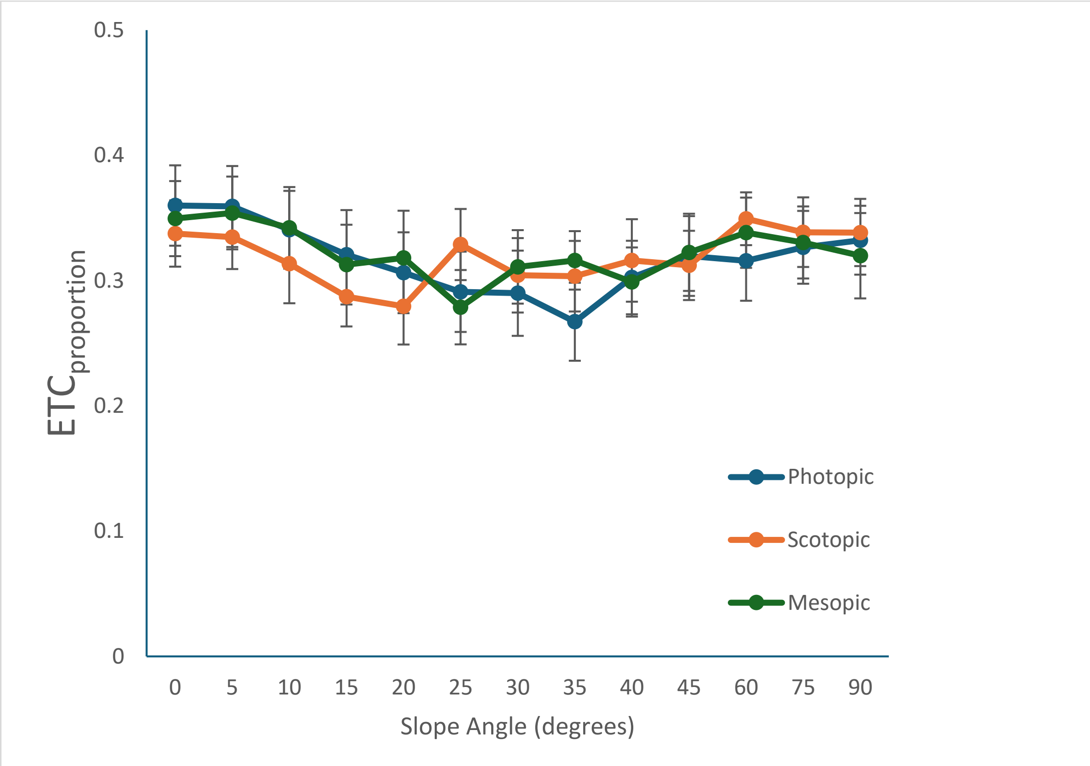
Note: The error bars represent 95% confidence intervals.

Figure A4. *Coefficient of Variation (CV) of Head Sway as a Function of Slope Angle and Lighting Conditions*



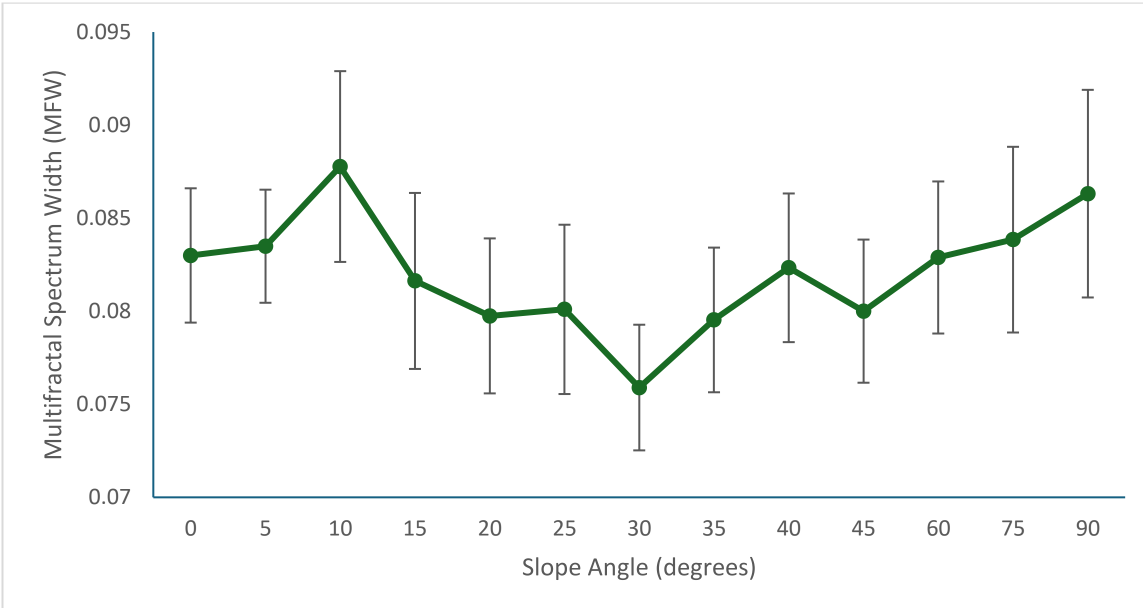
Note: Errors bars represent 95% confidence intervals.

Figure A5. *$ETC_{proportion}$(Head), Expressed as the Number of Steps Required to Homogenize the Time Series Divided by the Length of the Time Series, as a Function of Slope Angle and Lighting Conditions*



Note: Errors bars represent 95% confidence intervals.

Figure A6. *Multifractal Spectrum Width (MFW) Based on COP as a Function of Slope Angle Collapsed Over Lighting Conditions*



Note: Errors bars represent 95% confidence intervals.

APPENDIX C – IRB Approval Letter

Office *of* Research Integrity

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NOTICE OF INSTITUTIONAL REVIEW BOARD ACTION

The project below has been reviewed by The University of Southern Mississippi Institutional Review Board in accordance with Federal Drug Administration regulations (21 CFR 26, 111), Department of Health and Human Services regulations (45 CFR Part 46), and University Policy to ensure:

- The risks to subjects are minimized and reasonable in relation to the anticipated benefits.
- The selection of subjects is equitable.
- Informed consent is adequate and appropriately documented.
- Where appropriate, the research plan makes adequate provisions for monitoring the data collected to ensure the safety of the subjects.
- Where appropriate, there are adequate provisions to protect the privacy of subjects and to maintain the confidentiality of all data.
- Appropriate additional safeguards have been included to protect vulnerable subjects.
- Any unanticipated, serious, or continuing problems encountered involving risks to subjects must be reported immediately. Problems should be reported to ORI via the Incident submission on InfoEd IRB.
- The period of approval is twelve months. An application for renewal must be submitted for projects exceeding twelve months.

PROTOCOL NUMBER:	22-273
PROJECT TITLE:	Effects of Ambient Light Intensity on Affordance Perception
SCHOOL/PROGRAM	Psychology
RESEARCHERS:	PI: Tyler Overstreet Investigators: Overstreet, Tyler~Hajnal, Alen~Oliveira, Nuno~
IRB COMMITTEE ACTION:	Approved
CATEGORY:	Expedited Category
PERIOD OF APPROVAL:	28-Jul-2022 to 27-Jul-2023

Donald Sacco Jr.

Donald Sacco, Ph.D.
Institutional Review Board Chairperson

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