# How Light Intensity Affects Cyclic Plant Movement

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## Abstract

Some plants have adapted to fold their leaves according to a daily pattern. These patterns are an interesting trait in the natural world, especially because the reason for such an adaptation is not well understood and the effect of light intensity on movement has not been quantified. Movements of four experimental and one control Prayer Plant with independently controlled light sources are recorded with a time-lapse camera. The movement rate is extracted via a normalized frame-by-frame shift in pixel values near each plant. Increased light intensity increased the maximum movement rate and maximum movement amount, and no clear minimum light threshold was found. Also, peak leaf movement was seen 29.7 ± 2.1 minutes after exposure to light, which is similar to previous research that noted movement after 20 minutes.

## 1. Indoor Plant Lighting

Recent improvements to the accuracy, size, and cost of technologies such as sensors and LED lighting have increased interest in indoor agriculture. Specifically, the benefits of lower water usage, higher yield-per-square-foot, and decreased pesticide use provide rationale for indoor crop production over conventional outdoor methods [1]. There is a need for increased food capacity globally to feed a growing population, but the biggest drawback of indoor farming is its reliance on artificial light, which can contribute around 25% of operation expenses to large indoor vertical farms [2]. However, the exact mechanisms for plant responses to light are not fully understood, leaving a gap in our knowledge about building the most efficient artificial light systems for indoor plant production.

The common Prayer Plant responds to the daily sunrise and sunset by unfolding and folding its leaves. In an unfolded state, plant leaves have more direct exposure to light, which can increase photosynthetic activity [3]. Thus, if the Prayer Plant leaves are nudged into the unfolded orientation with proper lighting, plant energy can be produced more efficiently. Particularly, the rate and extent of plant leaf movement can predict when and where the leaves will move. Additionally, this study looks for a minimum light intensity that would prevent the leaves from unfolding in the morning, which would quantify the lower bound on useful levels of artificial light. Moreover, the existence of a minimum light intensity to trigger movement would back up past observations with quantitative data [4]. The experiment administers various intensities of LED lighting to a set of Prayer Plants, and records movement data with a camera. The timing of the leaf movement in the different trials is compared to results from previous research to verify the experiment's methodology and accuracy.

## 2. Background on Plant Nyctinastic Movement

Understanding nyctinastic movement, or movement controlled by circadian rhythms, is an essential part of our development of advanced and optimized plant cultivation. Nyctinastic movement is a visual indicator of where a plant is in the circadian rhythm, which many cellular processes depend on.

### *2.1 Understanding Plant Movement*

The types of plant movement vary: there is slow, growth-related movements taking several days (i.e. tropisms) or faster movement patterns taking hours (i.e. nastic movement). One form of tropic response is phototropism, which is the growth of plants toward the sun. While there are a variety of mechanisms at the sub-cellular level that contribute to tropic responses, the general movement can be characterized by “differential growth" – different growth rates in cells that form a curvature on the stem [5].

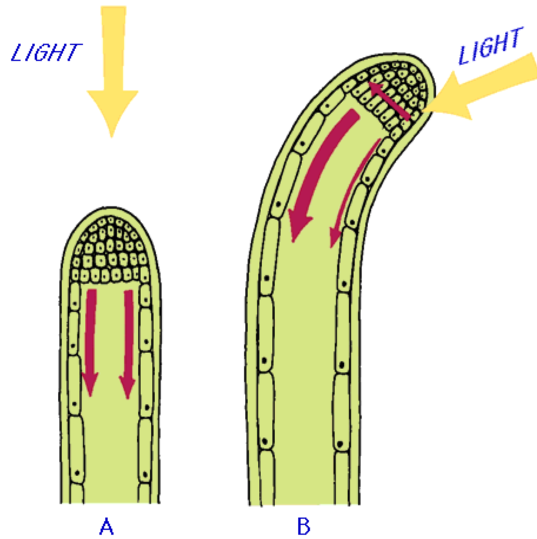


**Figure 1:** Phototropism in action. When the location of the sun shifts, the cells closer to the light shrink or replicate slowly, while the farther cells expand or replicate more rapidly. Adapted from reference [2].

The daily up and down movement patterns of *Maranta leucorneura* (common name: Prayer Plant), is a form of diurnal nastic movement. Dirunal movements are defined as occurring in a 24-hour period, and nastic movements are caused by stimuli such as light, but the movement response itself is not directed by the stimuli [6,7]. For example, Prayer Plants exhibit photonasty – light stimulated nastic movement. The sunrise is a unique signal that causes the leaves of the plant to drop down from their nighttime position, as seen in Figure 2, but movement direction is vertical regardless of where the light came from.

The movement of the *Maranta* plant are also nyctinastic, and most organisms have some sort of biological clock that triggers various cellular responses in the absence of changing conditions [8,9]. Cycles that last around 24 hours are referred to as circadian rhythms [8]. Importantly, circadian rhythms can adjust given the correct environmental cues, such as an earlier sunrise.

A variety of biological mechanisms contribute to plant movement, including variable cell growth and specialized motor cells. Most nastic movement is generated from pulvinus motor organs, which are cells located at the base of a leaf near the stem as shown in Figure 3 [4,11]. To move in a particular direction, the cells increase the concentration of various ions (such as potassium), which cause the cells to absorb water and expand.

**Figure 2:** Daily Prayer Plant movement. A Prayer Plant unfolds its leaves during the day and folds them up at night. This movement pattern in called photonasty as it is triggered by light, but the leaves do not move in the direction of the light source. The pattern can also be considered nyctinastic, as it happens in a circadian rhythm.

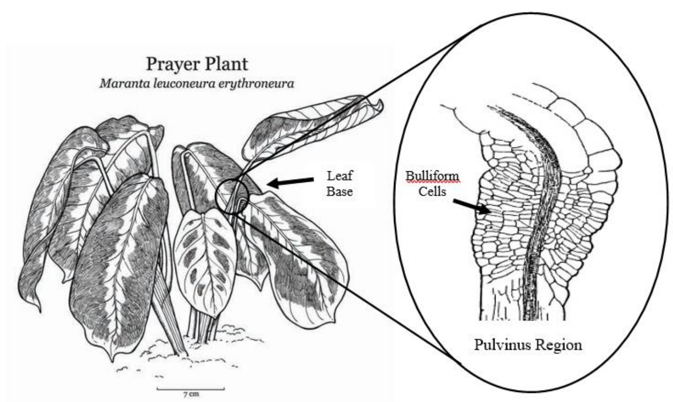


**Figure 3:** A close up of the pulvinus region. The pulvinus organ on a Prayer Plant appears at the base of a leaf, and consists of a variety of expanding Bulliform cells that can absorb large amounts of water to control the movement of the leaf stem.

### *2.2 Previous Studies on Plant Movement and Light*

The study of plant movement began early in the history of biology, with Charles Darwin writing a book titled “The Power of Movement in Plants” in 1888. Among other plant species, Darwin studied the *Maranta* genus, where he recorded the movements of leaves during extended periods of dark and light [4]. Although the circadian rhythm of the plant is around 24 hours, the leaves continued to show diurnal movement during a 36-hour period of darkness [4], indicating a strong innate sense of time.

Norman Dill, an undergrad at University of Delaware in 1960 extended this research by looking at the nyctinastic movements of Prayer Plants and potential movement mechanisms [4]. The experiment recorded the movement near the pulvinus region of individual leaves, while exposing the plants to specific periods of fixed-intensity light and complete darkness. Dill found that the *Maranta* plant leaves unfolded 20 minutes after exposure to light, and began a relatively slower folding process again 8-14 hours after the start of the light period [4]. In a trial where one plant was left in a dark cabinet for 7 days, the diurnal unfolding only occurred in the first 24 hours, after which the leaves stayed in the upright position [4]. This highlights the need of light for a sustained movement cycle, as well as the persistence of a circadian rhythm during a period without external stimuli.

Although the study provided significant insight on the movement patterns of Prayer Plants, Dill specifically noted that "no experiments have been conducted to determine the minimum light intensity required for diurnal rhythm to occur." Moreover, the study failed to analyze the rate of leaf movement, and instead chose to focus on the extent and direction of movement. Thus, an examination of the effects of light intensity on movement rate and the existence of any minimum threshold would provide new information about the nastic movement mechanisms.

## 3. Experimental Design

### *3.1 Design of the Plant Box*

The experiment quantified the rate of movement of Prayer Plants under different light intensities, so the experimental setup had to provide a healthy growing environment for the plants, ensure well-controlled experimental conditions, and facilitate easy data capture. The environment for the plants was critical so that they could respond naturally to environmental changes and maintain their health throughout the experiment. Likewise, due to the use of a camera for the main data collection, it was important to provide a high-contrast background and suitable lighting conditions to facilitate image processing later on. Figure 4 shows an overview of the experimental setup, with the control plant being isolated in the top box and the four experimental plants in the larger box below.

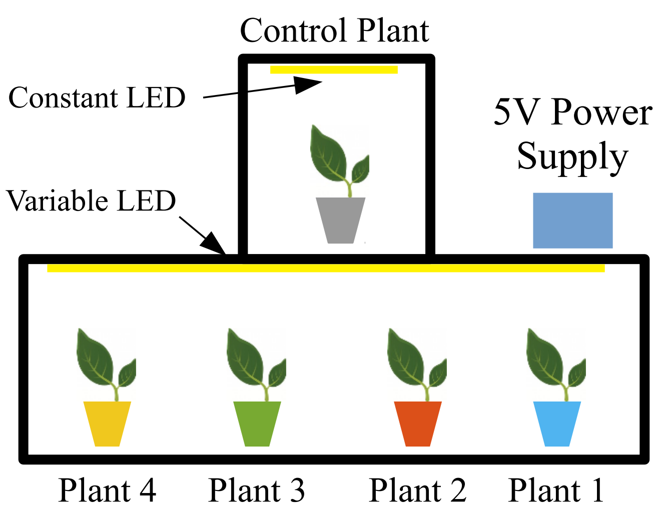


**Figure 4:** A front view of the experimental setup. The experimental plants are in the lower box, and the control plant is in the upper box. The LED light sources are controlled by a power supply and Arduino in the upper right corner. Also, the interior is painted white to maintain a good contrast with the plants.

The WS2812B Full-Spectrum LED lights in both boxes were independently controlled by an Arduino Nano, such that the control box maintained a sunlight-level brightness and the experimental box was adjusted to different light levels. The brightness of the lighting was measured in lux, which describes the lumens per unit area, a measurement which allows for better comparisons between different light sources. A Vernier Light Sensor (LS) was used to take light measurements at the start of each data collection period, which would always occur around the sunrise time of 6 AM as to avoid disrupting any other cyclic processes besides movement.

The Raspberry Pi 3 ran a script to take photos between 5 AM and 11 AM, which is roughly how long it takes for the leaves to unfold. The Pi contained an 8MP Camera Module V2 and the interior of both boxes were painted white to ensure a strong contrast with the green leaves.

The *Maranta leucorneura* plants, also known as Prayer Plants, were bought from Mahoney's Garden Supply in Brighton, MA. Prayer Plant care calls for moderate humidity, bright indirect light, and moist soil, so a humidifier was placed nearby when data collection was not in progress. Also, the plants were watered whenever the top of the soil felt dry, and normal indirect sunlight was used during the day instead of the LED lighting.

### 3.2 Data Collection

The collection of images occurred automatically each morning, but measurements of the LED lights and ambient room light had to be made manually at the beginning of each trial.

Three types of measurements were made: light intensity in the control box, light intensity in the experimental box, and ambient light intensity in the room. The Vernier sensor has three precision ranges. The 0-6,000 lux range was used for most of the box measurement and that range has 2 lux precision. The 0-600 lux range was used for the ambient light measurements because the light values were much lower, and that range has 0.2 lux resolution. The control box light intensity was chosen before any data collection began based on a series of measurements in the room where the lighting was qualitatively decided to be "bright indirect" light.

**Table 1:** The light intensities in the trials were based on a percentage of bright sunlight.

| Trial | Intensity (lux) |
|---|---|
| 100% (sunlight) | 820 |
| 120% | 980 |
| 50% | 410 |
| 25% | 200 |
| 15% | 120 |
| 7% | 60 |
| 1% | 10 |

### 3.3 Determining the Motion of Plant Leaves

The overlap of leaves in the camera frame and variable lighting throughout each trial made it difficult to extract velocity data for individual leaves. Thus, a "Motion Value" metric was created to quantify the differences in movement between trials. Each plant was cropped from the time-lapse video, and successive grayscale frames of each plant were compared for the whole video.

The Motion Value was defined to be the percent of pixels that changed between successive frames, such that stationary objects in the frame did not contribute to this value, while the moving leaves did. Additionally, the average brightness of the pixels was subtracted from each image to adjust for any changes in lighting during the trial. Figure 5 shows an extreme version of this frame-by-frame comparison, where the difference between the frames is the absolute value of the previous frame subtracted from the next frame.

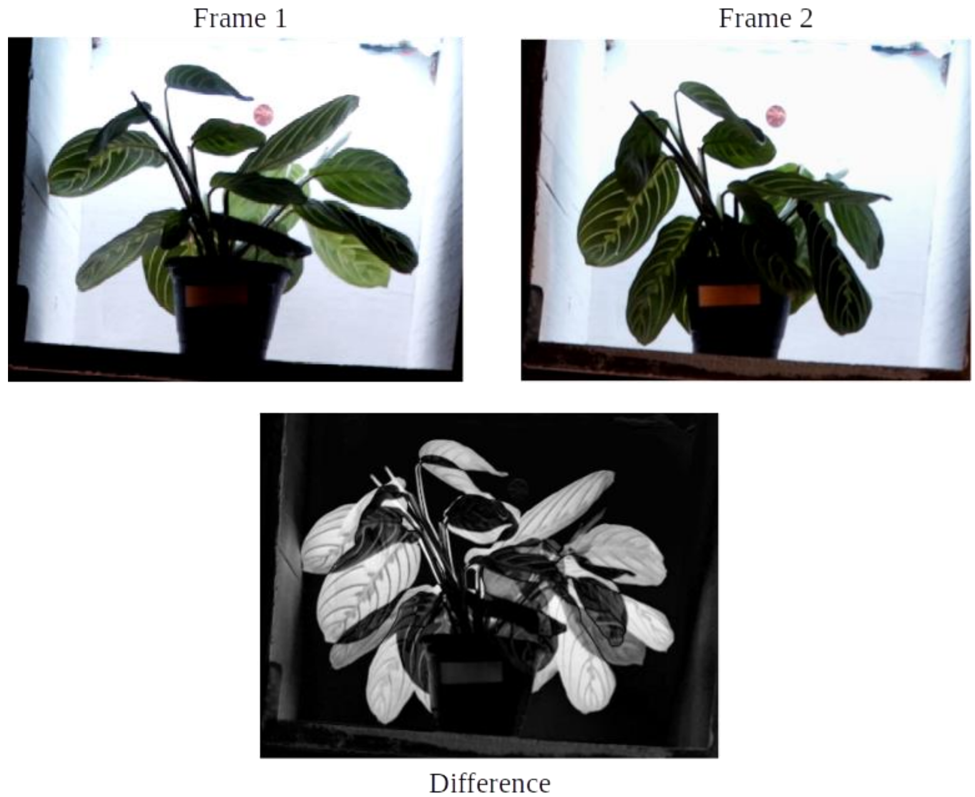


**Figure 5:** Motion Value frame comparison step. The small difference between successive frames can be characterized by the change in pixel values. Because the pots and background don't move, almost all the movements are related to the plant leaves. The white spots in the lower image show the points that changed between Frame 1 and 2, though these specific frames are a few hours apart to emphasize the results.

## 4. Results and Discussion

### *4.1 Extracting Motion Value*

The light sensor data was collected at the beginning of each trial, and time-lapse images were taken throughout the trial. Figure 6 shows an example of image data going from raw images to quantifiable movement data for Plant 3 in the 400 lux trial.

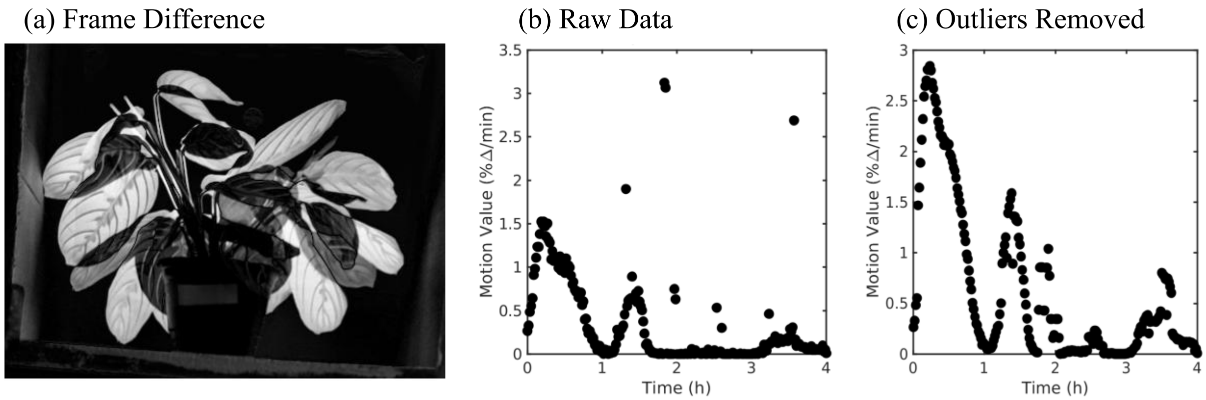


**Figure 6:** Raw data (a) from frame differences. A sequence of images is analyzed in MATLAB, which produces the plot shown (b). There are some outliers that obscure the underlying signal, but zooming (c) reveals an oscillating dampened signal that is quite different than what was predicted at the beginning of the study.

The movement pattern follows a sinusoidal shape. Averaging the hours from the start of the trial to the first local minimum as noted by the red circles in Figure 7, we find that the first oscillation finishes in 59.4 ± 4.3 minutes. No previous studies have mentioned an oscillatory movement rate, but Dill 1960 notes that the leaves begin to unfold 20 minutes after exposure to light. The 1-hour oscillatory motion rate would peak around 30 minutes, meaning that the most noticeable time of movement is close to that found in previous research.

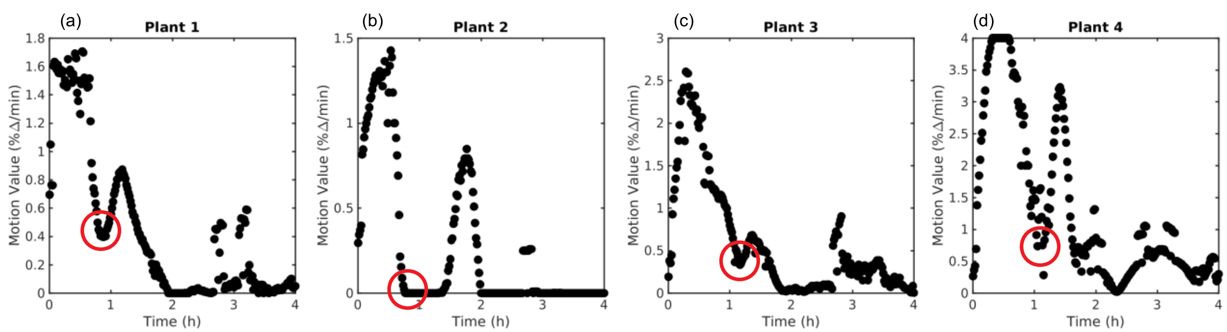


**Figure 7:** Motion values for all 4 plants during the 130 lux trial. The red circles show the time of the first oscillation, which occurred around 1 hour for every trial. The reasons for the oscillations are unknown, as it has not been discussed in prior research. However, this does give evidence that the first noticeable peak in movement occurs after 30 minutes.

### *4.2 Quantifying Movement Rate and Total Movement*

A running Riemann sum of each trial was calculated to show to total plant movement over time, which is seen in Figure 8.

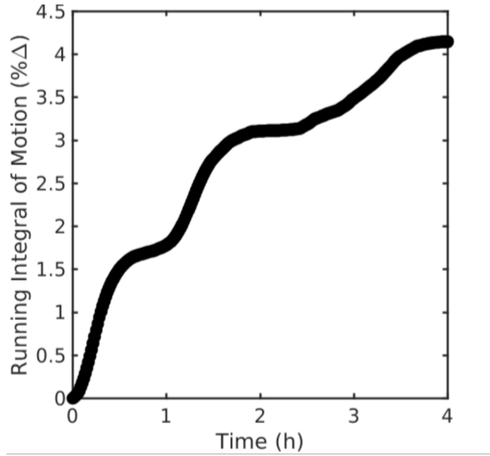


**Figure 8:** The motion value of each plant was integrated using a Riemann sum to get the total movement at different points in time. The slope of the sum changes due to the oscillatory pattern of the motion value.

Figure 9 shows the total movement after four hours in each trial of different light intensities. An asymptotic function $f(x) = a + \frac{b}{\sqrt{x}}$ was fit to the data, as there is likely a maximum amount of movement the plant can undergo each day.

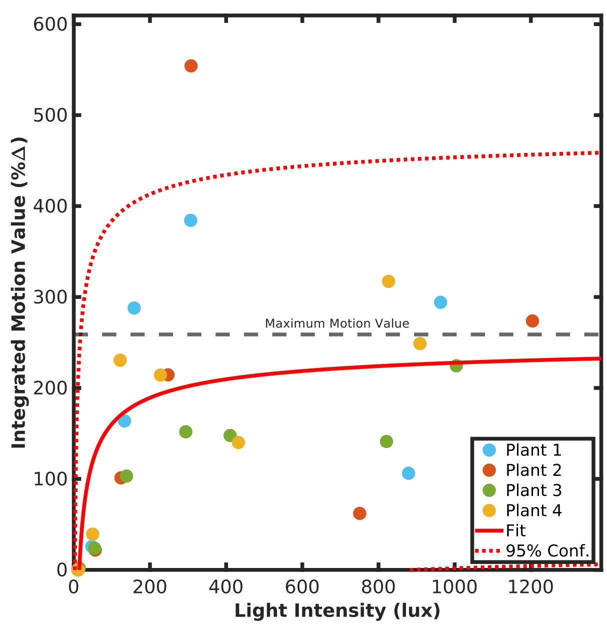


**Figure 9:** Total plant movement and light intensity. The equation $f(x) = a + \frac{b}{\sqrt{x}}$ was fit to the data, and the resulting parameters $a$ and $b$ were 259 ± 64 %Δ and -980 ± 490 %Δ, respectively. The dotted red lines represent the 95% confidence interval of the red fit line.

Originally, the equation $f(x) = a + \frac{b}{\sqrt{x+c}}$ was fit to the data, as the parameter $c$ would indicate a minimum threshold of light necessary to induce movement. However, this parameter was statistically insignificant so the function without the $c$ parameter was used instead. The resulting parameters $a$ and $b$ were 259 ± 64 %Δ and -980 ± 490 %Δ, respectively. Parameter $a$ has 25% uncertainty, so the maximum total movement of Prayer Plants is expected to be close to the data produced. However, $b$ has 50% uncertainty, indicating that the curvature or "ramp up" at lower light intensities is not as well know. Since $c$ was not used, there is no statistically significant minimum threshold of light that induced movement.

The maximum rate of motion was found by finding the maximum derivative of the Riemann sum in Figure 8. Figure 10 shows how the maximum rate of movement changed with different light intensities.

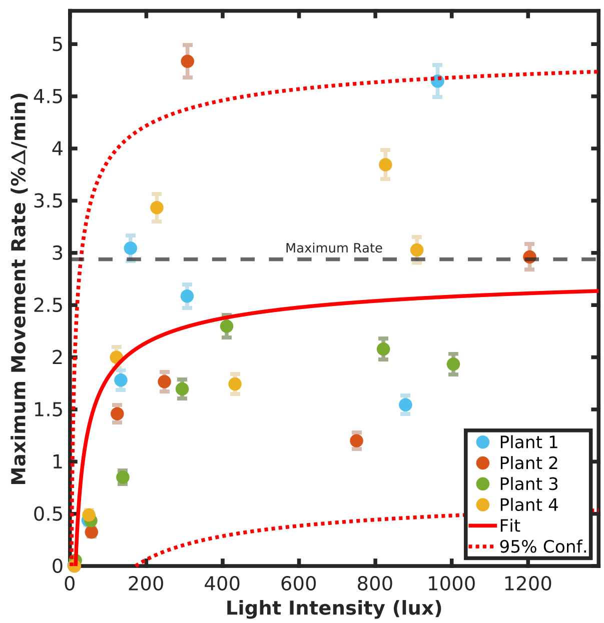


**Figure 10:** Maximum movement rate and light intensity. Using the same asymptotic fit, the resulting parameters $a$ and $b$ were 2.94 ± 0.60 %Δ/min and -11.3 ± 4.5 %Δ/min, respectively. Again, no minimum threshold of light was necessary to see a non-zero change in maximum movement rate. The dotted red lines represent the 95% confidence interval of solid red fit line.

The data was fit to the same curve as Figure 10. The resulting parameters $a$ and $b$ were 2.94 ± 0.60 %Δ/min and -11.3 ± 4.5 %Δ/min, respectively. The percent uncertainties of 20% and 40% for $a$ and $b$ indicate that the slope of the relationship is uncertain compared to the asymptote on maximum rate of movement.

### *4.3 Applications of Results*

The results suggest several metrics that could improve the effectiveness of artificial lighting and growth of Prayer Plants. Firstly, it was found that the plants show a peak movement rate after 30 ± 2.1 minutes. Shining light onto still folded leaves for the first 30 minutes may not be an efficient use of electricity compared to waiting until the leaves are a certain percentage unfolded.

Additionally, no minimum light threshold was found to trigger this movement, indicating that any initial light could be an extremely low energy source. Lastly, the asymptotic threshold provides insight onto the maximal effectiveness of light on the Prayer Plant. Light intensities near to asymptote yield minimal increases in plant movement during the unfolding period.

## 5. Conclusions

The results showed that there is no minimum threshold of light to trigger movement of Prayer Plant leaves and that movement rate increased with light intensity. The maximum movement rate (motion value) was asymptotically 2.94 ± 0.60 %Δ/min, while the maximum total movement was asymptotically 259 ± 64 %Δ, where the percent in both metrics is based on the percent of pixels that change frame-to-frame in the time-lapse.

Although more data should be collected to improve uncertainty bounds, the data suggests that plant movement can be triggered with minimal intensity light until the leaves are folded down it a more optimal position for photosynthesis. It takes 30 ± 2.1 minutes for to leaves to start moving at a noticeable rate, which is comparable to previous studies noting movement after 20 minutes [4]. This number gives a time estimate for when artificial lighting should be applied, such that light isn't wasted while the leaves are in the upright position.

More work is needed to increase the accuracy of the data collection and analysis methods, such as a more direct measurement of leaf movement and a quantitative use of the control plant when comparing data across trials. Also, a metric such as oxygen output, which is directly proportional photosynthetic rate, would produce results more applicable to indoor growing of Prayer Plants and other indoor plants.

This study provides a strong foundation for the experimental method and image analysis need for further research. Specifically, the movement or growth of other types of plants more commonly used in indoor agriculture could be quantified with a similar experimental setup. Coupled with the results from this study, the optimal light intensity could be predicted with greater accuracy to make growing indoors more efficient. Overall this study advances our understanding of the Prayer Plant and the development of quantitative research on the effects of lighting on plant movement.

## Acknowledgments

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