**Research Question: How does changing the length of a pendulum from (21.5, 18.5, 15.5, 12.5, and 9.5 cm ±0.05cm), affect its damping effect measured through the change in potential energy when no external force is applied to the bob initially?**

## Background

The research aims to investigate the effect on the length of a pendulum on the damping constant. The experiment results can be measured through the changing height it reaches after each oscillation.

A pendulum will undergo simple harmonic motion if no external forces are acting on it. The relationship between time period, length and gravity can be calculated using **Equation 1** below:

$$T = 2\pi\sqrt{\frac{L}{g}}\ \text{(Equation1)}$$

$T$ is the period of oscillation,

$L$ is the length of the pendulum, and

$g$ is the acceleration due to gravity.

$\theta \leq 10°$ for small angle approxiamation



However, if external forces exist, the equation won't be suitable anymore because damping will exist (Ip). The term damping is used to describe reducing oscillation amplitudes caused by the irreversible removal of vibratory energy (Adnan Akay and Carcaterra). The process of damping keeps the same time period and frequency while decreasing the amplitude as we are able to see from **Figure 1**.

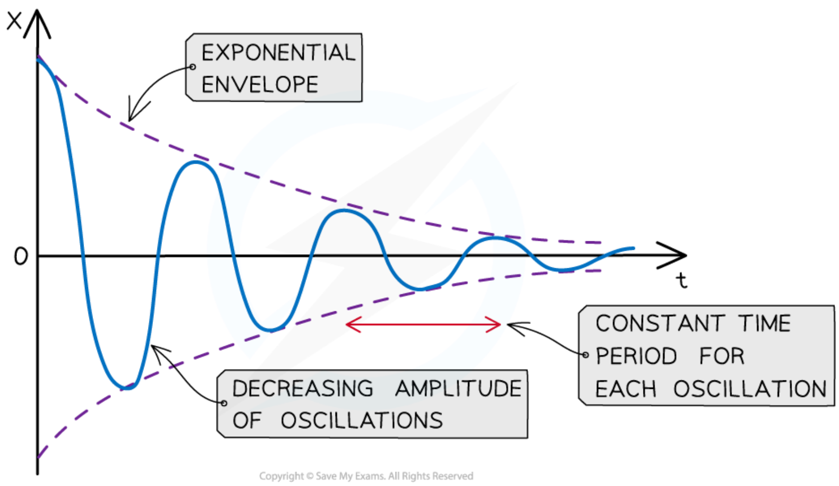



Figure 1 Damping ("The Effect of Damping | SL IB Physics Revision Notes 2025").

Theoretically, in a homogeneous linear elastic material, pendulums can travel infinitely without a change in amplitude ("Damping Effects"). However, this is impossible in real life. The pendulum will ultimately stop because the elastic energy within the pendulum will be transferred to the surroundings, which can be understood by the effect of a damping mechanism like air resistance and friction. As a result, even though theoretically a change in length won't affect the damping constant as it does not exist, but in reality, a longer pendulum will have a larger damping constant.

The principle behind the derivation is that changing the length will affect the time period of the pendulum according to Equation 1. A longer length will result in a longer time period and thus a higher amplitude of oscillation which may cause the pendulum to experience more significant damping effects due to increased exposure to damping mechanisms like air resistance. The longer the exposure time the pendulum has with air, the more opportunity it has with air resistance and a more pronounced damping effect.



In summary, while the direct relationship between the length of the pendulum and the damping constant may not be straightforward, changes in the length of the pendulum can indirectly influence damping by affecting the period of oscillation and thus the interaction with air resistance.

To calculate the damping constant, factors in **Equation 2** below need to be considered:

$$\zeta = \frac{c}{2\sqrt{mk}} \text{ (Equation 2)}$$

$\zeta$ is the damping constant,

*c* is the damping coefficient,

*m* is the mass of the oscillating system, and

*k* is the stiffness of the system.

As a result, the same apparatus is better to be used in repetitive experiments because factors like mass and stiffness should be controlled.

Factors like the medium in which the oscillation occurs should also be controlled because force of friction is different in different mediums. For example, water has fluid friction and air has air resistance. In this experiment specifically, the medium is only air as damping effects in air is useful to be investigated and the experiment can be conducted more easily in air.

## Hypothesis

When increasing the length of the string, the speed and gravitational energy will decrease accordingly, and the damping constant would decrease accordingly.

## Methodology

**Table 1** below lists the independent variable and the dependent variable.

| Variables | Details |
|---|---|
| Independent | The length of the pendulum (21.5, 18.5, 15.5, 12.5, and 9.5cm± 0.05cm). This will be manipulated by measuring a desired length using a ruler. |
| Dependent | Gravitational potential energy, representing the damping effect, measured through the changing heights of every ten oscillations |

Table 1 The independent variable and the dependent variable.

**Table 2** below lists the controlled variables:

| Controlled Variables | Why and how to control the variable |
|---|---|
| Mass of the bob | According to the Background, $\zeta = \frac{c}{2\sqrt{mk}}$, the mass of the bob affects the damping constant. The mass of the bob will be kept constant by using the same bob throughout the experiment. |
| Medium | According to the Background, different damping mechanisms will affect the damping constant. For example, water and air have different friction to the bob. It must be controlled so that the change of speed is solely due to the change of length of pendulum. The medium will always be air. |
| Initial amplitude | Different initial damping amplitude will result in different damping behavior such that larger initial amplitude leads to a more significant damping effect, a greater air resistance and a more pronounced damping effect. The initial amplitude should be measured at a consistent degree at 10 degrees. |
| Initial speed | Different initial speeds will result in different total energy and different time period and frequency. Thus, it must be controlled so that the change of speed is solely due to the change of length of pendulum. The initial speed will be controlled at 0 m/s, which means no external force is applied. |
| Period | As a factor which plays an important role in affecting the damping constant, period must be controlled so that the change of speed is solely due to the change of length of the pendulum. It helps maintain the consistency in the experiment and allows a fair comparison between trials. |

Table 2 Controlled variables.

**Table 3** below lists the apparatus needed in the experiment.

| **Apparatus** | **Quantity** | **Uncertainty** |
|---|---|---|
| Metal bob | 1 | / |
| Stopwatch | 1 | ±0.001s |
| Ruler | 1 | ±0.5cm |
| Pendulum (with length options of 0.311, 0.376, 0.457, 0.559, and 0.711 meters) | 1 | / |
| Electrical balance | 1 | ±0.001g |
| Protractor | 1 | / |

Table 3 Apparatus list.



**Procedure**

Set up:

1. Measure and record the mass of the pendulum bob using an electrical balance.

2. Adjust the pendulum length to the desired values using a ruler (21.5, 18.5, 15.5, 12.5, and 9.5 cm±0.05cm)

3. Use a protractor to set the initial amplitude of the pendulum to 10 degrees (±0.5°)

4. Verify that the period of oscillation remains constant for all pendulum lengths. Adjust the pendulum length as necessary to maintain a constant period.

Experimental Procedure:

1. Start recording at a stationary level.

2. Release the pendulum bob from the same initial amplitude for each length of the pendulum.

3. Observe and record the time it takes for the pendulum bob to complete 10 oscillations

4. Repeat steps 1 to 3 for each pendulum length.

5. After each trial, record the decrease in maximum height it reaches at every oscillation.

6. Calculate the potential energy of the pendulum bob at every oscillation for each trial.

The set up of the investigation is shown in Figure 2 below:

Figure 2 set up.

Data Analysis:

1. Plot graphs showing the decrease in speed and change in potential energy over time for each pendulum length.

2. Calculate the damping constant (ζ) for each pendulum length using appropriate formulas or regression analysis methods.

3. Analyze the relationship the between the pendulum length and damping constant based on the collected data.

**Safety, environmental and ethical issues:**

As the experiment does not contain wastage of resources or emission of gases, there are no obvious environmental and ethical concerns. Apart from that, as the bob is made from metal, it might hit people by accident, leading to related injuries. The experiment should be conducted in a safe environment and unrelated people should keep distance from the apparatus.

**Raw data**

**Qualitative data-what is observed when the length of string changes**

As the length of the pendulum decreases, the heights it reaches are lower and the time periods to complete one oscillation are shorter.

**Quantitative-Raw data table-**Table 4 below shows the raw data collected.

Table 4: length of string; initial height of the bob; and height of the bob at the tenth, twentieth, and thirtieth oscillation

| Length (cm±0.1cm) | Trial # | Initial height (cm±0.1cm) | Height at 10th oscillation (cm±0.1cm) | Height at 20th oscillation (cm±0.1cm) | Height at 30th oscillation (cm±0.1cm) |
|---|---|---|---|---|---|
| 21.5 | 1 | 29.5 | 27.6 | 26.4 | 25.3 |
| | 2 | 32.5 | 29.5 | 26.4 | 25.3 |
| | 3 | 31.0 | 28.2 | 26.6 | 24.6 |
| | 4 | 29.4 | 27.1 | 25.8 | 25.0 |
| | 5 | 30.1 | 28.2 | 26.0 | 24.3 |
| 18.5 | 1 | 34.5 | 31.5 | 29.9 | 28.6 |
| | 2 | 38.2 | 35 | 33.1 | 32.9 |
| | 3 | 37.5 | 33.4 | 30.5 | 30.0 |
| | 4 | 36.5 | 32.6 | 29.4 | 26.1 |
| | 5 | 36.3 | 35.0 | 30.4 | 28.6 |
| 15.5 | 1 | 38.5 | 34.1 | 31.1 | 30.5 |
| | 2 | 36.6 | 35.1 | 34.2 | 33.9 |
| | 3 | 36.8 | 35.5 | 34.9 | 34.0 |
| | 4 | 37.6 | 35.8 | 34.4 | 33.4 |
| | 5 | 36.7 | 34.5 | 32.6 | 31.8 |
| 12.5 | 1 | 41.0 | 39.3 | 38.2 | 36.5 |
| | 2 | 41.4 | 40.6 | 39.1 | 37.2 |
| | 3 | 38.4 | 36.4 | 35.3 | 34.4 |
| | 4 | 38.4 | 36.4 | 35.6 | 35.0 |
| | 5 | 38.6 | 36.6 | 35.2 | 34.6 |
| 9.5 | 1 | 41.4 | 40.1 | 38.4 | 37.4 |
| | 2 | 41.5 | 40.6 | 38.2 | 37.2 |
| | 3 | 40.9 | 39.9 | 39.0 | 38.3 |
| | 4 | 41.3 | 39.9 | 38.8 | 38.4 |
| | 5 | 41.8 | 40.7 | 39.6 | 38.6 |

**Sample Calculations**

Now, all the height values need to be converted into potential energy to see the changing damping effect brought by changing the length of the pendulum using **Equation 3** below:

$GPE = mgh$ (Equation 3)

$GPE$ is gravitational potential energy, in joules (J)

$m$ is the mass of the bob, in kilogram (kg)

$g$ is the gravitational acceleration constant, in newtons per kilogram (N/kg)

$h$ is the height above the ground, in meters (m)

In my investigation, the table is when $h = 0m$ and the height above the ground is defined as the height above the table.

A sample calculation based on an initial height of length of 21.5 cm is given below.

The average value of 5 trials of the initial height of length of 21.5 cm is calculated:

$$\text{Initial height at 21.5 cm} = \left(\frac{29.5 + 32.5 + 31.0 + 29.4 + 30.1}{5}\right) \text{cm} = 30.5 \text{ cm}$$

Units should be converted into standard units



$$\text{mass} = 50\text{g} = 0.05\text{kg}$$

$$\text{Average height} = 30.5\text{cm} = 0.305\text{m}$$

GPE is calculated

$$GPE = mgh = 0.05 \times 9.81 \times 0.301 = 0.1496025 \text{ J}$$

Error propagation of GPE

$$\Delta h = \frac{\text{Max} - \text{Min}}{2} = \frac{(0.325 - 0.294)}{2} = 0.0155 \approx 0.02$$

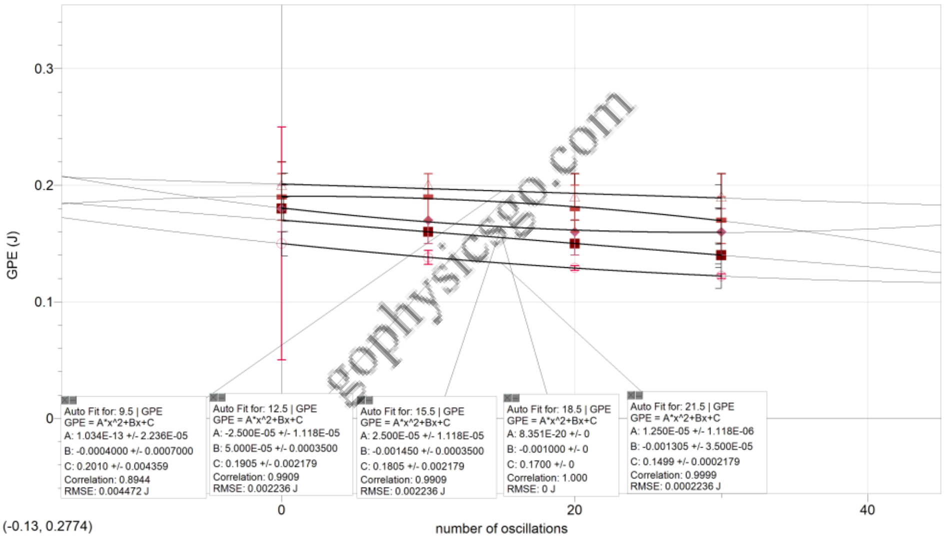
$$\frac{\Delta GPE}{GPE} = \frac{\Delta h}{h} + \frac{\Delta m}{m} + \frac{\Delta g}{g} = \frac{0.02}{0.305} + 0 + 0 = 0.0656 = 6.6\%$$

$$\frac{\Delta GPE}{GPE} \times GPE = 6.6\% \times 0.1496025 = 0.00981 \approx 0.01$$

$$GPE = 0.15 \text{ J} \pm 0.01 \text{ J}$$

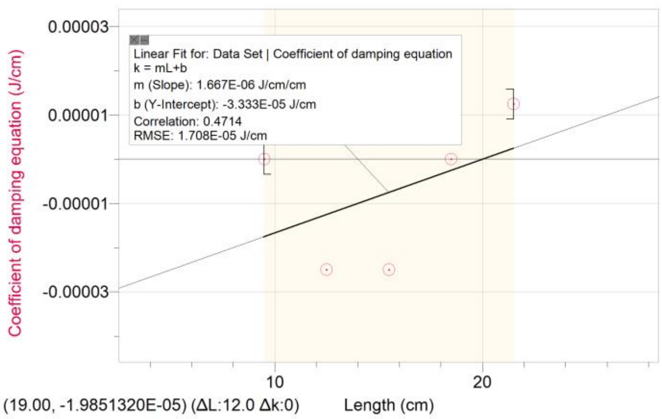
Using the procedures described, Table 5 below shows the processed data, Graph 1 shows the difference of potential energy curve at different oscillations, and Graph 2 shows the change of coefficient of the curves in Graph 1 at different oscillations. The coefficients are used to show the relationship between the length and damping because it represents the rate of changing potential energy. Besides, by plotting coefficients instead of the entire curve, the effect of IV on DV is more obvious.

| Table 5: Processed data table | | | | |
|---|---|---|---|---|
| Length (cm±0.1cm) | Initial GPE (J) | GPE at 10th oscillation (J) | GPE at 20th oscillation (J) | GPE at 30th oscillation (J) |
| 21.5 | 0.15 | 0.138 | 0.129 | 0.122 |
| 18.5 | 0.18 | 0.16 | 0.15 | 0.14 |
| 15.5 | 0.18 | 0.17 | 0.16 | 0.16 |
| 12.5 | 0.19 | 0.19 | 0.18 | 0.17 |
| 9.5 | 0.20 | 0.20 | 0.19 | 0.19 |





Graph 1 number of oscillations vs. potential energy.




Graph 2 Length vs coefficient of damping.

## Conclusion

The purpose of this investigation is to calculate the effect of length of pendulum on the damping constant. The hypothesis is that as length decreases, an increase in friction force will decrease speed but there will be a negligible effect on the damping constant. The processed data was plotted and the results reveals a messy increasing relationship between the length of the string and the maximum height reached. The gradient of the result is $1.667\times10^{-6}$, meaning every decrease of every centimeter of length of pendulum will result in a $1.667\times10^{-6}$ decrease in gravitational potential energy. The calculation does not support the hypothesis that length won't affect the damping constant but showing a positive relationship between them. As the gradient of Graph 1 is generated by Logger Pro directly, there is no uncertainty for the y-axis in Graph 2. So, the worst fit line of Graph 2 is not able to be drawn.

What causes this unrelated conclusion? According to Stack Exchange, the length of the pendulum will affect the damping, however, different properties of the media is the most important factor in influencing the damping. In other words, the difference of the damping effect is more obvious when the pendulum is placed in different media.



**Percentage uncertainty of the slope:**

If the percentage uncertainty is larger than 10%, the data is not precise.

If the percentage uncertainty is smaller than 10%, the data is precise and reliable.

However, as the percentage uncertainty is not able to be calculated and there is no relationship between the independent and dependent variable, the preciseness of the data is unable to be determined.

## Evaluation

Because there is not really a standard value for damping of different pendulum lengths in air, the experimental value of the gradient can be any value because there is no standard value. The possible reason of the discrepancy might not be due to the weakness and limitations of the experiment, but we still can evaluate the process of the experiment. At the same time, there are some strengths of the experiment which led to the success of the results.

| Strength | Significance |
|---|---|
| Five trials per length | Repeats of experiment trials reduce human error and random errors such as inaccuracy of angle of the string pulled, height of the amplitude measured and so on. |
| The values are collected by analyzed videos instead of using eyes directly | By checking the recorded video, the peaks of the height reached in every trial are able to be determined. This reduces possible systematic errors that values detected by human's eyes directly are usually smaller than the actual values because we cannot always determine the height at the exact point. |

**Weakness and limitations with their consequences**

Further improvements can be still linked to collecting heights of the bob because the frame of the camera is limited. For example, even though the method of using recorded videos is good, the uncertainty is big as a thick linear line is used to determine the height with respect to the ruler. The method of collecting data is shown in Figure 3 below:



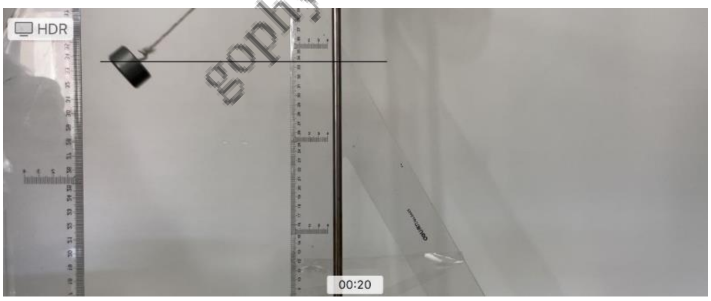



Figure 3: data collection.

To improve this random error, we can change the equipment to video analysis to Logger Pro or a sonic motion detector to obtain a value of heights more frequently by collecting data more times per second. In this way, as the tracking system is more accurate, the values of height can be more precise.

Another weakness of the experiment is that the direction the bob is moving is not certain and not able to be controlled. This, to an extent, reflects that the controlled variable is not being controlled well. The initial angle of the string, even though it can be measured each time, cannot be exactly the same, resulting in different directions of the bob. Also, because the string length is adjusted by rolling the string on the iron stand, the pivot that the string is connected to the stand is moving. Specifically, when the string swings upwards, the pivot moves up a little bit; and vice versa. And the movement of the pivots sometimes causes collision of the string to the stand, letting to bob to change direction. Thus, the bob can feel frictional forces from multiple directions, resulting in an uncertain frictional level. To improve this, we can cut the string instead of roll it on the iron stand, maybe also use a clamp to make a fixed end instead of a free end to eliminate the changing directions.

Besides, another limitation of the experiment is that the range of independent level is limited. The range is only between 9.5 to 21.5 centimeters, which is chosen because of convenience. This small range of data results in limited application of the conclusion. In other words, the results might be different in other IV range that we haven't investigated. To improve this, the experiment can be repeated at other lengths of the string to conduct further investigations.

## Works Cited



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