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An Illuminating Exploration on the Intensity of Sound and Light Waves as Related to the Inverse Square Law

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Abstract

The purpose of this experiment was to investigate the propagation of sound and light waves and the inverse square law. The measured intensity of sound or light at some distance from a source is known to be inversely proportional to the distance squared from the source. Sound propagation was investigated by measuring sound intensity at a range of distances from a speaker. Light propagation was investigated by measuring light intensity at a range of distances from an iPhone flashlight. First, it was found that sound propagation obeys the inverse square law. As shown in Figure 3, the experimental data meets the criteria to claim a good fit to a $\frac{1}{r^2}$ relationship. This report contains discussion of the methods employed to minimize uncertainty for the sound data, such as varying different power input parameters, and selecting a test space that reduces sound reverberations. Second, light propagation was found to follow a decreasing nonlinear fit, but the inverse square relation to distance was not able to be verified given the small uncertainties and a slight systemic trend in the residuals plot. This experiment has significance in the fields of optics, acoustics, electromagnetism and astrophysics.

1 Introduction

Johannes Kepler was the first to propose that certain physical phenomena obey an inverse-square law in relation to distance. In 1604, he proposed that the intensity of light emitted from a point source obeys such a law and later went on to argue that gravity also obeys the same relation [1]. Many physical phenomena related to the propagation of forces or energy obey the inverse square law. Some examples include Newtons Law of Gravitation:

$$g = \frac{GM}{r^2}, \tag{1}$$

and Coulomb's Law of Electromagnetism:

$$E = \frac{KQ}{d^2}. \tag{2}$$

The inverse square law applies when a force or energy is radiated equally in all directions outward from a point source in a 3-dimension space. As the energy or force gets farther away, it gets spread out more and more, leading to a decrease in intensity due to a front covering a larger surface area. This law arises from the mathematical fact that the surface area of a sphere centered at a point source in three dimensions is directly proportional to the square of the radius.

This experiment consists of examining the inverse square law using the propagation of both sound and light waves. Sound and light waves are both known to propagate according to the inverse square law:

$$I = \frac{s}{4\pi r^2}, \tag{3}$$

where I is the intensity, s is source strength (power for sound and luminosity for light) and r is the distance from the point source of sound [2]. The instruments used in this experiment will measure the amplitude of the sound waves such that relative sound intensity can be calculated. The intensity (I) of a sound wave is notably proportional to the Amplitude (A) of the sound wave squared as seen in the equation:

$$I = 2\pi^2\nu^2A^2, \tag{4}$$

so,

$$I \propto A^2. \tag{5}$$

The instruments used to measure light intensity will more simply measure white light intensity directly.

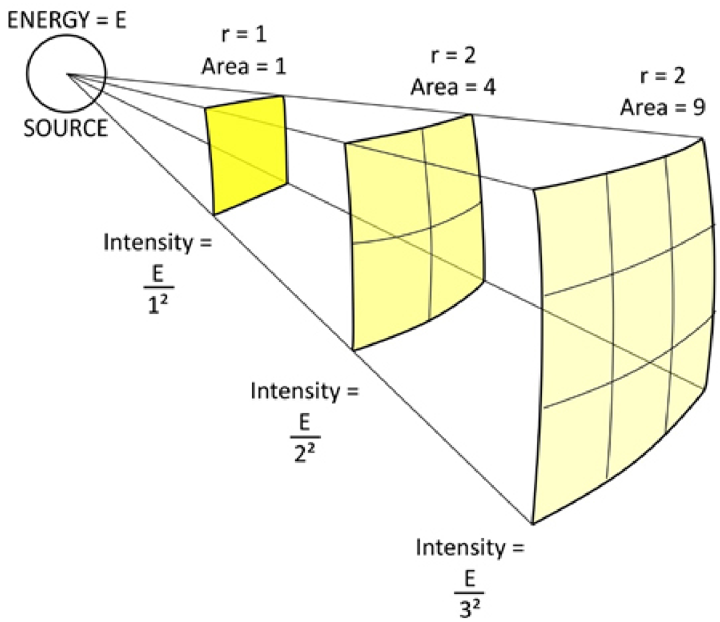

Figure 1: A visual representation of the inverse square law [3]

Although this experiment will limit its focus on the inverse square law as it relates to everyday levels of sound and light, the inverse square law appears in all kinds of physical phenomenon. From the electrostatic repulsion of two electrons, to the blast of a supernova, the inverse square law determines nearly all the universe's transfer of energy and forces in open space. For this reason, this experiment has significance in the fields of optics, acoustics, electromagnetism and astrophysics.

2 Materials

Point Source Speaker, Interstate F31 function generator (EQ5319), RODE Dual channel wireless Microphone and Receptor (EQ6797), RIGOL oscilloscope (EQ6179), iPhone Flashlight, Light Sensor (EQ 6725), Meter Stick, BNC Cables and splitters, Small Wooden Blocks to use as stands for sources and sensors, Dark Room and Quiet Room (Dark Room in Rutherford Physics Building).

3 Methodology

3.1 Measuring Sound

1. The speaker and channel 1 of the oscilloscope were connected directly to a voltage power source, set to a sine wave of $V_{pp} = 10V$ at 25 kHz, using a split-er. The input amplitude and frequency were held constant throughout the entire experiment.

2. Channel 2 of the oscilloscope was connected to sound sensor receiver which in turn was connected to a microphone/sensor via Bluetooth

3. Speaker and microphone were propped up on wooden stools, a meter-stick was used to find the exact distance between speaker and microphone.

4. The microphone was positioned at different discrete distances from the speaker ranging from about 5cm to 90cm. At each distance, V_{max} of the microphone output signal, or channel 2 (corresponding to amplitude) was read off the oscilloscope using the measure tool.

5. As the value V_{max} would constantly fluctuate about every half second , the value for the amplitude was quoted as the mean of all the values shown in a five second window.

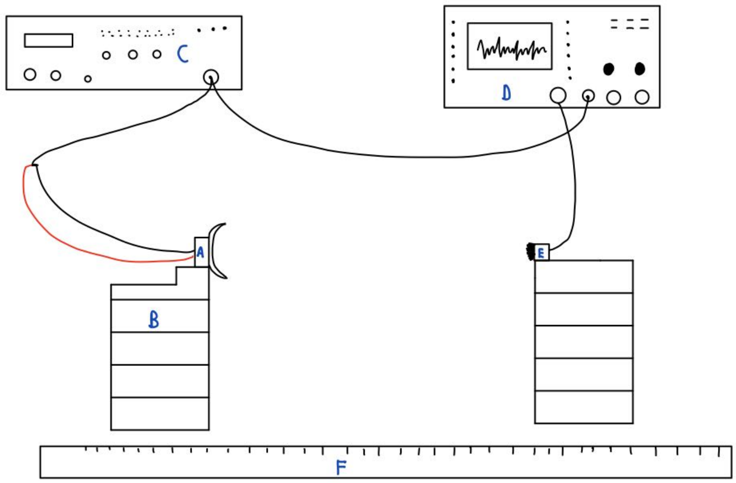

Figure 2: A sketch of the experimental setup, where A is the speaker, B is a block/stool on which we set our speaker/microphone to be levelled, C is a power generator, D is an oscilloscope, E is a microphone and F is a meter.

3.2 Measuring Light

1. The spotlight sensor was connected to Capstone on the laptop with a cable.
2. iPhone and spotlight sensor were propped up on wooden blocks positioned next to the meter stick (similar to sound setup in figure 2). Spotlight sensor was ensured to be carefully aligned with iPhone flashlight.
3. The spotlight sensor was positioned at different discrete distances from the iPhone flashlight ranging from about 5cm to 80cm. At each distance, white light intensity was recorded using Capstone software.

4 Results

4.1 Sound Intensity

From equation 3, one can see that $I = \frac{S}{r^2}$, meaning the intensity is dependent on only one parameter, a constant S . A built-in function called curve_fit was used to conduct a weighted non-linear fit to find said constant S.

4.1.1 Set-up 4

To obtain the best possible results, data was taken with four different sequential experimental set-ups, each set-up improving on the errors of the previous. The journey leading to Figure 3 (set-up 4) is detailed in Appendix 1.The fourth and final set-up bore the most precise and unobstructed data out of all the different experimental designs. The standard error was found using np.std([array]), where the array was all the different value of V_{max} recorded within the 5 second window.

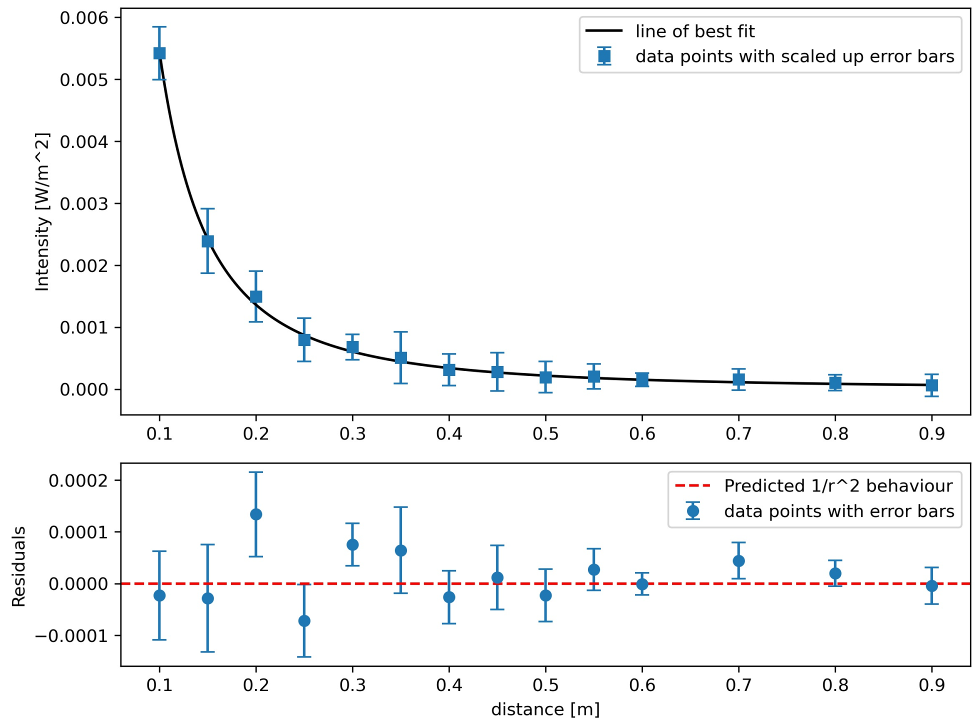

Figure 3: Sound Intensity vs Distance; error bars are scaled by 5 in main plot

4.2 Light Intensity

In this part of the experiment, one trial was done as described in *Methodology* and the results are displayed below in figure 4. Note the trend in residuals plot indicates that the inverse square may not be the best fit, since a random Gaussian distribution about the zero line is not observed.

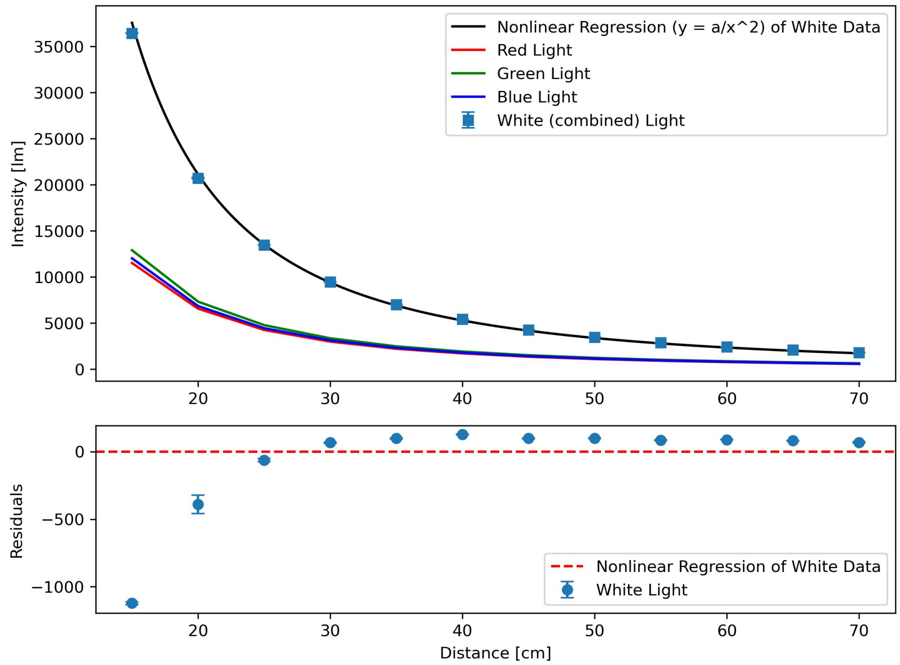

Figure 4: Intensity of Light From Point Source Measured At Varying Distances By a Spotlight Sensor

5 Discussion

5.1 Sound

The results of this experiment clearly indicate that the intensity of a propagating sound wave obeys the inverse square law. As seen in Figure 3, the sound intensity recorded by the microphone at different distances dropped off at the predicted rate with distance in accordance with the inverse square of the distance. As shown in Appendix 1, repeating the sound data collection with an improved methodology produced more precise data overall. Initially the uncertainty on intensity was on the order of $\pm 0.002 Wm^{-2}$, as seen in figure 5. For set-up 2 and 3, uncertainties were decreased to an order of $\pm 0.0005 Wm^{-2}$ (figure 6 and figure 7) by lifting the speaker and microphone off the table to reduce vibrations from speaker travelling through the table to microphone and causing significant fluctuations (recall: the uncertainties on these measurements were calculated from the observed variance in the voltage values). Switching to a sinusoidal generated sound over a pulse does not appear to have reduced uncertainty but may have had an effect in removing systematic error for a more accurate measurement.However, when the input was switched from sound pulses to a continuous wave an interesting phenomenon appeared. As seen in figure 7, the intensity around 10 and 45 cm is much greater than the expected value. This is likely due to constructive interference from the sound waves reflecting off the walls. Up to set-up 4, all measurements were taken in a very small room (Rutherford Dark room), which would interfere with the assumption that the sound waves drop off to zero after they pass the speaker (no reflection). At certain spots in the dark room, there would be spikes in the amplitude of the microphone signal. To counter this Set-up 4 was conducted in a much larger room, and produced the most precise and accurate measurements with uncertainties on the order of $\pm 0.0002 W m^{-2}$ (figure 3).

The data collected in set 4 (Figure 3) is the most precise of the propagation of sound waves. Therefore, the data from this trial was used to confirm or deny whether the experimental data behaved in a way expected from the inverse square law. As is visible in the residuals plot in figure 3, ten out of the fourteen data points are within one standard deviation of the best fit line. This equates to approximately 71 %, which is in accordance with the value of 66 % that is expected if the data is a good representation of the proposed fit. It is also clear, that the data points follow a random Gaussian distribution about the zero line. Therefore we can say that our experimental data does obey the inverse square law.

5.2 Light

The results of the light section of this experiment does not strongly align with the predicted inverse square fit. Although the intensity of white light does drop off in a nonlinear way as expected, a plot of the residuals of this fit show a trend (figure 7). This indicates that an inverse square fit is not suitable for this data otherwise the estimated uncertainties on light intensity have been underestimated. The uncertainties were calculated similarly to that of sound intensity; the sensor took over 30 measurements at each distance and the standard deviation of these measurements was taken to be the uncertainty at that distance. One possible additional source of error is a misalignment of the spot light sensor. When the sensor was not perfectly aligned with the iPhone flashlight the intensity was observed to drop dramatically. When moving the light sensor between distances, small deviations in alignment may have produced significant errors. Future experiments should strive to ensure precise alignment of light and sensor. Alternatively an ambient light sensor in a dark, non-reflective room could be used to remove the issue of alignment to the light source.

6 Conclusion

This experiment has shown the inverse square law to be verifiable in the example of propagating sound waves over a distance. Performing the experiment in a larger quite room to minimize sound reverberations off walls played a large roll in producing more precise measurements. This experiment has successfully observed the effects of the inverse square law, which is known to describe nearly all phenomena in which information (e.g. energy, force) is propagating radially outward in our universe. This experiment less conclusively demonstrated light intensity obeys an inverse square relation. The residuals plotted in figure 7 definitively show a trend, therefore, goodness of this fit is suspect. Although the spotlight sensor used is a highly precise instrument, an ambient light sensor may remedy possible sources of error involved with minute misalignment's in the spotlight sensor

References

1. Johannes Kepler, Ad Vitellionem Paralipomena, quibus astronomiae pars optica traditur (Frankfurt, (Germany): Claude de Marne heir Jean Aubry, 1604), page 10. 1

2. BC Campus. UNIVERSITY PHYSICS VOLUME 1. 17.3 Sound Intensity. Accessed April 7th 2022. https://opentextbc.ca/universityphysicsv1openstax/chapter/17-3-sound-intensity/ 1

3. https://www.imagesco.com/nuclear-science/geiger-counter/experiment-4.html 2

4. Inverse square law. (n.d.). Energy Education. https://energyeducation.ca/encyclopedia/Inversesquarelaw

A First Appendix

A.0.1 Set-up 1

The speaker and the sound sensor were both placed on the table. The power input was to set to pulse mode, and the amplitude was recorded as V_{pp}. This run was to gauge whether the data was roughly following a inverse square law relationship.

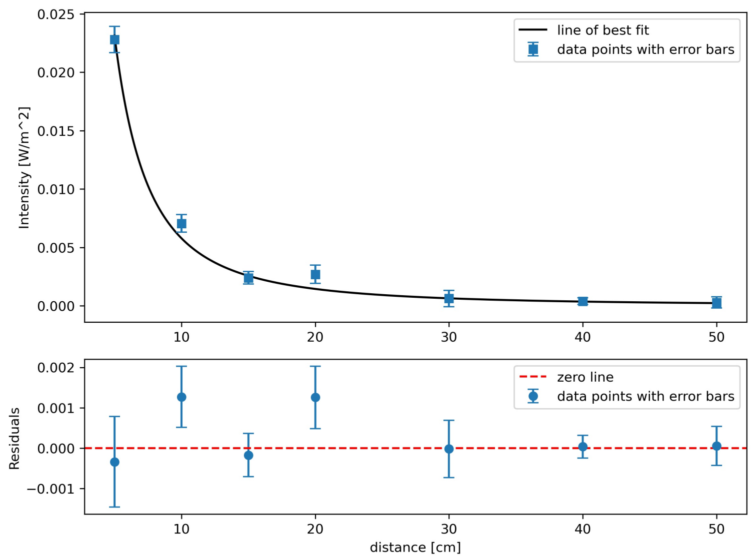

Figure 5: Intensity vs Distance Run 1

A.0.2 Run 2

For run 2, both the speaker and the sensor were placed on equally leveled blocks to minimize any potential error caused by vibrations through the table or sound waves reflected off the table. The power input was to set to pulse mode.

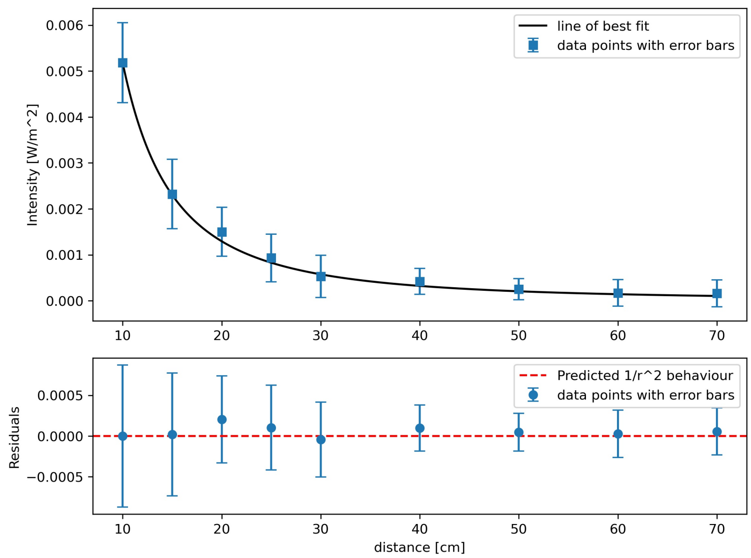

Figure 6: Intensity vs Distance Run 2: raised speaker and sensor

A.0.3 Set-up 3

The third set of runs was performed under the same conditions as run 2, except that the power input was changed to a normal sinusoidal waveform rather than sending out sound pulses. This would have increased the accuracy of the results since the pulse mode only sends out discrete pulses of sound, rather than a stable continuous output.

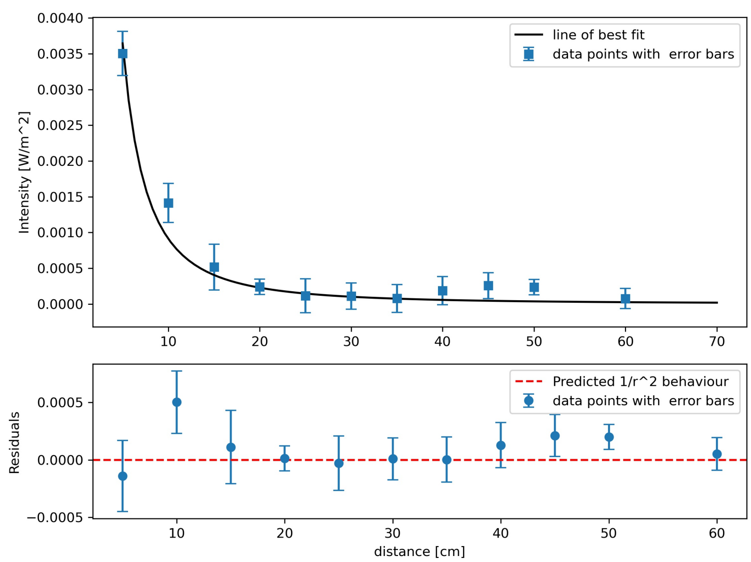

Figure 7: Intensity vs Distance Run 3: Continuous wave input

A.0.4 Set-up 4

As seen in figure 7, the intensity in run 3 around 10 and 45 cm is greater than the expected value. This effect was the result of systemic error in the setup of which is discussed further in the discussion. However, the solution to this issue was to move the apparatus to a larger room, and set the speaker and sensor on stools of equal height. This set-up is what proved to give the most accurate and precise results.

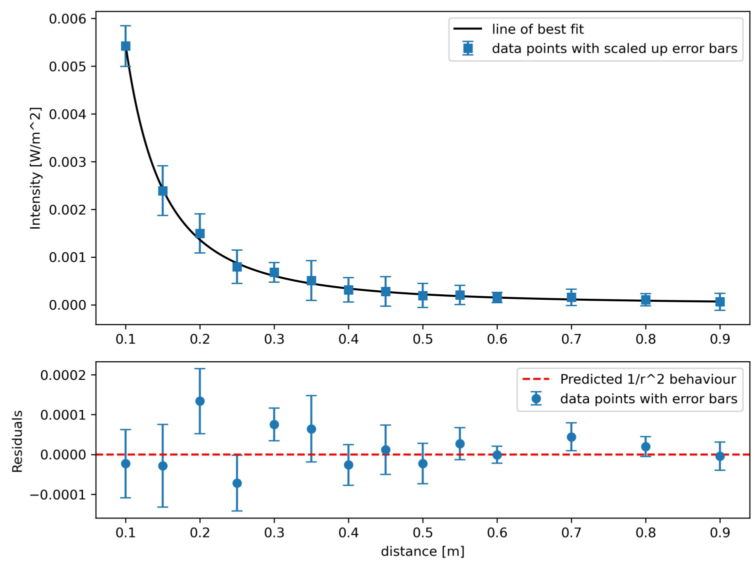

Figure 8: Intensity vs Distance Run 4: Large Room

B Second Appendix

Using the inverse square model produced by curve fit, a power output for the speaker was calculated to be 324W. This was found through the following steps:

$$I = \frac{P}{4\pi r^2}$$

$$\text{Where, } I = 2\pi^2\nu^2A^2$$

$$\therefore 2\pi^2\nu^2A^2 = \frac{P}{4\pi r^2}$$

$$A^2 = \frac{P}{8\pi^3\nu^2r^2}, \text{ Let } \beta = \frac{P}{8\pi^3\nu^2}$$

$$\therefore A^2 = \frac{\beta}{r^2}$$

Using curve fit, β was found to be 5.445×10^{-5}

$$\therefore \frac{P}{8\pi^3\nu^2} = 5.445 \times 10^{-5}$$

$$\therefore \frac{P}{8\pi^3(24000Hz)^2} = 5.445 \times 10^{-5}$$

$$P = 324.15W$$

Although a calculation of the actual sound power output of the speaker was not possible due to lack of information concerning the specs of the speaker used, one can assume it would be around 324.15 W.

C Author Contribution

All authors M.B, R.M, M.M and E.H contributed and read over all parts of this report equally. R.M completed matters concerning the sound part of this report, whereas M.M did the data analysis for the light part of this report. M.B and E.H did additional writing of the abstract, introduction, materials and methodology and conclusion. The discussion was done by all 4 members and the lab book was done by M.B.