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The effects of geometric regularity in spider web architecture on the capture of prey

Abstract

Webs allow spiders to trap prey without spending the energy needed to chase it down. There exist many different types of web architectures, which exhibit high levels of structural diversity. Two very common shapes are the spiral orb web and the sheet web, which mainly differ in architecture - spiral orb webs have a high degree of geometric regularity while sheet webs are completely irregular. An advantage of geometric regularity in any structure is the ability to evenly disperse kinetic energy, therefore reducing the likelihood that the structure will succumb to instability and break. In this study, I compared the number of prey caught in orb webs and sheet webs to see if their architectural differences could affect the number of prey they can trap. I monitored spider webs near my house and compared the average number of prey trapped in orb webs and sheet webs. The results were statistically significant, indicating that webs with geometrically regular architectures can trap more prey. Ultimately, this study can give us insight into how the structures and material properties of webs balance each other to work as functioning traps for prey, and may help reveal new possibilities for the application of spider silk analogues.

Introduction

In nature, spiders use their silks for several tasks, including web-building, wrapping of prey, protection of their offspring and as a lifeline to ensure a safe escape from predators (Romer, 2008). Web-building is among the most important, as they allow spiders to trap prey without any extra energy expenditure (Romer, 2008). About 50% of all spider species build webs, and more than 130 different shapes of webs have been identified (Romer, 2008). There are seven distinct types of silks that exist, but most spiders produce four to eight of them from discrete abdominal glands that each have a different property. Some are characterized by their strength, others by their elasticity or rigidity, and one for its stickiness (Romer, 2008). This complement of different silk types covers a wide range of mechanical properties, which are further enhanced by web architecture.

The architecture of orb webs in particular is quite interesting - it is the only web shape that exhibits such a high degree of geometric regularity (Harmer, 2011), which is necessary to guarantee stable equilibriums and allows the structure to act as a unified system (Chen, 2015). The orb web is typically composed of flexible adhesive spiral threads, the main function of which is prey retention, supported by an outer scaffold made of strong and stiff threads that keep the sticky silks in place (Soler, 2016). The structure works to dissipate the colliding prey's energy and transmit the impact load outwards (Zschokke, 2002).

Figure 1: Comparison of orb (left) and sheet (right) web architecture. Orb webs they have evolved to cover the largest area possible with the least amount of silk, which is best achieved with a planar web. Their basic shape consists of radial arms and spiral meshwork. Sheet webs are built horizontally, are three-dimensional, and have no observable geometric pattern. Photos by Brent Opell (Hawthorne, 2003)

This unique architectural feature of orb webs has been investigated by many, given their superior performance. A 2013 study by Sensenig measured the energy absorbance of orb webs by launching balsa wood blocks and ping-pong balls weighing around 300 mg. Their results showed that orb webs' energy absorbance actually improves as the speed of colliding materials increases, up to a speed of 4 m/s. Comparing this to the average flight speed of flies weighing 45 mg of approximately 2.5 m/s (Sensenig, 2013) that they would encounter in the wild, these results clearly attest to the incredible strength of orb webs. They appear to function as traps that maximize the probability of stopping the largest possible prey (Sensenig, 2013). They can easily trap smaller prey as well, but they provide little energetic gain to the spider (Sensenig, 2013). In short, the design of orb webs favours the capture of larger and faster flying prey - the silks seemed to get tougher as materials were launched faster at the web (Sensenig, 2013). Therefore their unrivalled strength as prey traps is due not only to the exceptional mechanical properties of the silk, but also to their brilliant structural arrangement.

Web-building spiders rely on the critical interplay between web structure and the biomechanical properties of their silks to successfully capture prey. In this study, I wanted to compare the prey-capture ability of orb webs to that of another type of web that is not geometrically organized at all - sheet webs. I hypothesized that if orb webs are more geometrically regular compared to sheet webs, then orb webs will be able trap more prey because they will disperse the kinetic energy of colliding prey and therefore better resist damage to the silks.

Methods

I conducted this study in Burnaby, British Columbia during the months of October and November. I monitored spider webs near and around my house and tracked the number of prey captured in them.

First, I classified the shape of the web as orb or sheet, then I counted the number of prey. To control for the fact that the spiders may not eat their prey right away after capturing them, I counted the number of prey every three days. Checking every three days gave the spider enough time to consume its prey, ensuring that I was not counting the same prey more than once. I considered anything trapped in the web or that that the spider was consuming as prey. I also chose to observe the webs at 8:00 pm PST because spiders are nocturnal and would thus be more active after dark compared to during the day. The only materials used were a camera and flashlight to closely examine the webs in the dark, as well as statistical analysis software.

I obtained a sample size of n =3 for orb webs and n = 2 for sheet webs, which I observed on nine days, for a total of 27 data points for orb webs, and 18 for sheet webs. I calculated the average number of prey in orb webs and sheet webs and compared them. Because I was comparing two averages, it was appropriate to conduct my statistical analysis using a two-sample t-test and a 95% confidence interval. The null hypothesis states that there is no difference between the average number of prey caught in orb webs compared to sheet webs, and the alternative hypothesis states that there is a difference.

Results

The average number of prey trapped in orb webs was 13.30, and the average for sheet webs was 7.22. The two-sample t-test yielded a p-value of less than 0.0001 and a 95% confidence interval of (3.29, 8.89). The results were extremely statistically significant at a significance level of 0.05, so we reject the null hypothesis.

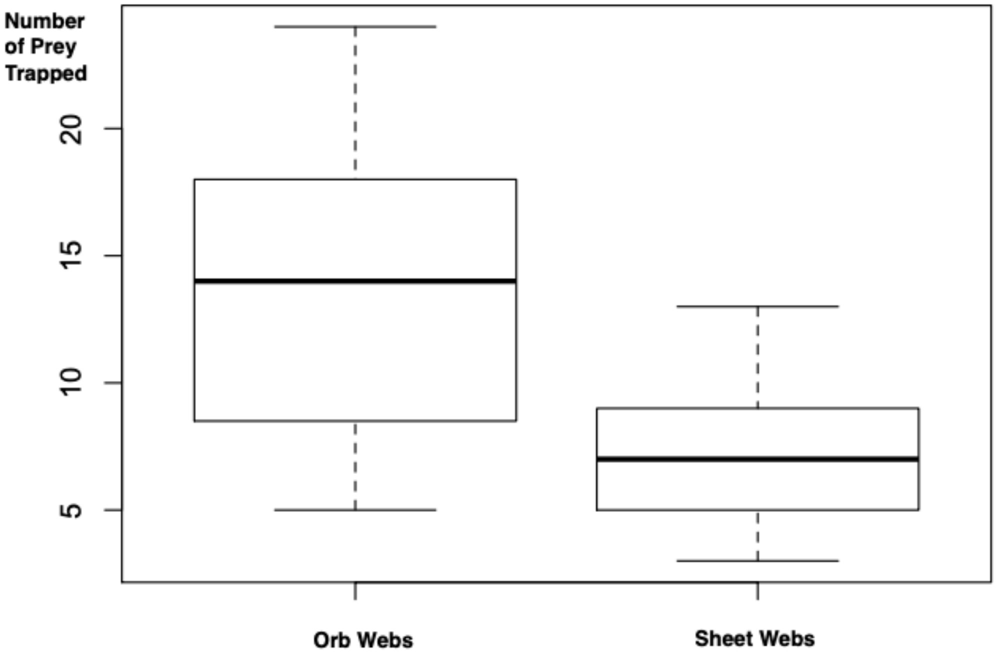

Figure 2. Boxplot of number of prey trapped in orb webs compared to sheet webs created in R Studio. Horizontal bars at the top and bottom of each plot correspond to the largest and smallest number of prey observed for each web.

As for qualitative observations, I kept track of any damage that occurred to the webs throughout the study. I observed a small hole in one of the sheet webs, but the damage seemed to have been fixed when I checked again three days later. Plus, on two separate occasions, very strong winds and heavy rain occurred, but did not cause any observable damage or tears to any of the five webs.

Discussion

The results indicate that orb webs are better at catching prey than sheet webs, and since the main difference between them is their architecture, it is feasible to suggest that it is the reason for their enhanced ability to trap prey. The advantage of orb webs' prey-catching abilities lends itself not only to their geometric regularity, but also to the fact that they are built vertically. Like sheet webs, orb webs can have extending threads to catch prey from above and below, but only orb webs are able to intercept the flight paths of prey (Zschokke, 2002). Orb webs have an additional advantage, where insects struggling to get away and dropping down are held back by the lower half of the web, whereas in horizontal webs, prey can completely fall through (Zschokke, 2002). The tear observed in the sheet web also suggests that the web may not have been able to completely distribute the energy of the colliding material evenly. This lends further support to the hypothesis that orb webs are more resistant to damage because of their geometric regularity.

However, because this study was not done in controlled lab conditions, we must be cautious in generalizing these results. Firstly, the locations in which the webs were built were quite different and may have influenced the results. The sheet webs were both built around rose bushes with large branches and thorns. It's possible that the damage in the sheet web that I observed was caused by either that or by small animals, such as squirrels, racoons, and birds, that could have reached them. In comparison, the orb webs were built quite high off the ground, decreasing the risk of disturbances by other plants and animals. Also, my method of checking the webs every three days may not have been entirely reliable. Although spiders are likely to eat the prey that they catch within a day (Romer, 2008), it's possible that they may have waited longer, and an instance of counting the same prey more than once may have occurred. Lastly, using a larger sample size will increase the accuracy of my results.

Another study by Soler (2016) further attests to the integral role that geometric regularity plays in orb webs' strength by showing that even slight variations in geometry dramatically weaken their prey-capture abilities. This indicates that web architecture greatly affects structural performance, as the strength of the web depends heavily on the optimal distribution of the silk (a limited and valuable resource for the spider) and on the appropriate positioning of these threads (Soler, 2016). This teamwork between the silks' properties and arrangement makes orb webs well-adapted to handle strain and impact forces with ease.

But regardless of shape, the silks that make up both web types nonetheless have outstanding mechanical strength and elasticity (Gu, 2020). Spider silks have long been admired and appreciated for their properties, so much so that scientists have been working for years to recreate them in a man-made silk analogue. The strength of spider silks are incomparable to that of other natural and synthetic fibres. Distinct spider silk threads can absorb three times more energy than Kevlar, one of the sturdiest materials on weight-to-weight basis (Harmer, 2011), are twice as flexible as nylon (Gu, 2020), yet are thinner than human hairs. Its elasticity and strength gives the silk a high damping coefficient, allowing for a quick recovery when disturbed (Sensenig, 2013). The intrinsic toughness of spider silk can be combined with the features of the orb webs' architectural design to make it an exceptional material for a myriad of applications, ranging from athletic wear to military purposes.

A simple application for spider silks is found in textiles - protective clothing made from spider silk has good breathability, can absorb sweat, and is more resistant to wear and tear (Gu, 2020). Silks can also be used to make biodegradable bottles and bags to replace single-use plastics (Gu, 2020). On larger scales, spider silks can be used for high-velocity industrial or military applications, such as ballistic energy absorption, ropes, and parachutes (Sensenig, 2013). Body armour and parachutes made from spider silk are extremely light weight and can better absorb impact forces and improve the strength of the material (Gu, 2020). Silks can also be applied to the shells of equipment such as tanks, aircraft, and satellites, or act as a protective cover structure for military buildings (Gu, 2020). Lastly, spider silk analogues will have important application in the biomedical field. One of which is to build artificial blood vessels. A significant disadvantage of today's artificial blood vessels is their instability and lack of vascular resistance (Dastagir et al., 2020). Spider silks can be used to improved the physical properties of artificial bloods vessels. Dastagir et al. (2020) developed a new type of artificial blood vessel using natural spider silk as a supporting matrix. Results showed that this artificial blood vessel has extreme biocompatibility (i.e. will not produce a toxic or immunological response when exposed to living tissue), has mechanical properties equivalent to those of natural blood vessels, and can make cells adhere, differentiate, and proliferate (Dastagir et al., 2020).

All of these applications require the silks to be arranged in such as way that allows kinetic energy to be evenly dispersed: body movements cause strain on clothing fabrics, parachutes need to withstand drag forces, and blood flow exerts pressure on arterial walls. The even dispersal of energy can be achieved with geometric stability and symmetry. The interplay between the biomechanical properties and the macro-structure of spider webs must be considered, as they will be key in the development of silk analogues and their applications. For further study, we can measure the energy absorbance of sheet webs (like in Sensenig's 2013 study) to closely observe their recovery when disturbed and compare it to that of orb webs.

Conclusion

The unmatched toughness and resilience of spider silk can be further enhanced by highly geometrically regular web architectures, as it allows webs to evenly disperse kinetic energy of colliding material and prevent damage. Results of this study shows this, as orb webs were able to catch more prey than sheet webs, on average. In the production and application of spider silk analogues, the architectural and geometric features of spider webs should be considered to optimize their properties.

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