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What Would the World Be Like to a Borrower?

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Abstract

The plausibility of the existence of miniscule, human-like creatures known as "Borrowers" in Studio Ghibli's film, *The Secret World of Arrietty*, is called into question as a variety of factors prevent such life from being viable. Humans, scaled-down sixteen-fold isometrically, would encounter many problems at Arrietty's scale, having reduced hearing and sight, extremely high voice pitch, and inability to maintain normal body temperatures.

Introduction

In Studio Ghibli's 2010 animated film, *The Secret World of Arrietty*, the titular character, Arrietty, and her family belong to a population of miniscule human-like creatures called "Borrowers" [1]. As with the film's source material – Mary Norton's novel, *The Borrowers* – they are portrayed as exactly like humans, simply at a smaller scale, being shown to see, hear, speak, and live as humans [1,2].

Such scaled-down humans, however, cannot exist. Biology simply does not scale directly – there are reasons why elephant-sized mice and vice-versa do not exist. This paper will explore why, and use this reasoning to analyse what differences would exist between life- and Borrower- sized humans.

The Physics of Scale

Despite what the film suggests, uniform scaling can only realistically occur over a limited range. Because not all factors are extrinsic, the environment – and the forces that dominate which – are largely different over different scales [3]. The film was able to convey this well for physical systems. In Arrietty's world, surface tension is much more apparent – instead of flowing, liquid pouring from a Borrower-scale teapot forms droplets that collect at the spout's mouth, similar to a medicine dropper (Figure 1) [1]. This is because surface tension is intrinsic and therefore independent of scale. The force due to surface tension along a circular mouth is given by equation 1:

$$F_\gamma = \pi d \gamma \qquad \textbf{(1)}$$

where d is spout diameter and γ is surface tension. Setting this equal to the force of gravity gives the maximum droplet mass shown on equation 2 [4]:

$$m = \frac{\pi d \gamma}{g} \qquad \textbf{(2)}$$

This means that as diameter scales down, droplet mass scales by the same factor [5]. Arrietty's mass, however, would scale down at the cube of that factor, accounting for three dimensions [3]. Thus, the droplet mass relative to a human of the same scale increases by the factor squared. Given that Arrietty is approximately 10cm [1] while a typical Canadian female is 162.3cm [6], this corresponds to an apparent 263-fold increase in the droplet size – imagine holding a quarter-litre droplet!

Figure 1) A frame from *The Secret World of Arrietty*, showing a larger apparent surface tension [1].

Isometry vs Allometry in Biology

The existence of these intrinsic properties also affects the scaling of biological systems. Proportion-preserving scaling, called isometry, does not result in biologically viable life for the same reasons as pouring tea differs [7]. Properties scale differently depending on how many dimensions are geometrically relevant. The most apparent example is the skeletal system with bone strength dependent on cross sectional area, two dimensions, and weight dependent on volume, three dimensions. The discrepancy is evident – at doubled scale, quadrupled strength must support eight times the weight. Larger animals account for this by having proportionally larger bones – a textbook example of allometry, scaling with differing proportions [8]. In this aspect, Arrietty is actually overbuilt, with 16 times as much skeleton than she requires. While not directly a problem, excess resource usage would be selected against by Darwinian selection [9].

At 16 times smaller, however, Arrietty would have 16 times as much surface area relative to mass. This means she would lose heat much faster than humans do. Smaller mammals correct for this by having faster metabolisms relative to body size [10]. At the same metabolic rate as humans, however, Arrietty would have to wear thick coats to maintain healthy body temperatures.

Sound Localization

Most animals locate sound sources using differences in the sound wave as it reaches each ear. Since the speed of sound is the same on any spatial scale – 331.29m/s – events that occur at some distance away will always take the same amount of time to reach the listener [11]. Half the distance, and that time is halved.

Hair cells detect sound by oscillating in response to the sound wave. For frequencies below 1.5kHz, hair cells can oscillate in phase with the sound wave, relaying auditory signals to the Medial Superior Olivary Nucleus (MSO) [12]. Because of the distance between the left and right ear, a time delay, known as the Interaural Time Difference (ITD), is introduced. As signals from both ears arrive at the MSO, the ITD determines which MSO neuron activates, allowing for sound localization [12].

Because this method relies on a time difference, and the speed of sound in air is intrinsic, it therefore relies on the distance between the two ears. Arrietty's scaling factor of approximately 16 corresponds to this distance being scaled down by the same factor. The human brain is able to detect ITDs at a microsecond resolution, corresponding to a minimum left-to-right ear distance of 0.33mm. While Arrietty is not quite that small, with the same ITD resolution, she would have poorer sound localization – a factor of 16 worse than humans.

Localizing sounds over 1.5kHz uses a slightly different method, but nonetheless relies on head size [13]. As a result, Arrietty would have a much harder time hiding from humans than depicted in the film – she would barely be able to figure out which direction they were coming from!

Vocal pitch

Much like a pair of violin strings, humans produce sound through vibrations in the vocal folds – a set of tendons attached to cartilage on either side of the larynx. Depending on how tensed the vocal folds are, their length and therefore the pitch changes. As such, the vocal folds can be approximated as strings with the fundamental frequency corresponding to the wavelength twice their length [14].

In humans, women with vocal folds tensed to 6.5mm produce a fundamental frequency of approximately 440Hz [15]. If Arrietty's vocal folds are 16 times shorter, this scales to approximately 7000Hz. This translates to a four octave pitch increase given the logarithmic nature of sound perception, making her speaking voice much higher than any human speaking naturally. She would therefore be unable able to converse with the humans as she does in the film.

Vision

Eye size among mammals tends to be nearly invariant and independent of scale. This is because eye functionality is dependent on the size of the eye and not its size relative to the organism – larger eyes collect more light, up to a certain point [16]. Therefore, with scaled down eyes, Arrietty would be nearly blind as very little light would enter her eyes.

Conclusion

Borrowers, as depicted in the film, could not exist as a variety of both physical and biological factors make such a creature biologically unviable. Any human isometrically scaled down 16-fold would experience a variety of problems, having reduced hearing and vision, extremely high voice pitch, and be unable to maintain normal body temperatures.

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