JOURNAL OF
EMERGING INVESTIGATORS

Article

The effect of circumference on the segregation of objects in a mixture

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SUMMARY

The size segregation problem refers to the phenomena of larger particles rising to the top of a mixture of variously sized items seemingly against gravity. Upon reviewing the literature on the size-segregation problem, also known as the trail mix quandary, we realized that the reported findings did not account for the apparent adverse behavior of hollow items. Despite geophysical implications, such as erosion sediments, explanations regarding hollow items are necessary to ensure more precise distribution of nanoparticle substances throughout various systems. Additionally, the size segregation of irregularly shaped particles has not been clearly addressed. To address these limitations, we put forth a hypothesis that circumference, rather than size, dictates the arrangement of falling objects. We found that the distribution of hollow particles could be better predicted with a revision of the size-segregation theory. The key observation that motivated us to propose the revision to the model was that hollow beads sometimes trended toward the bottom of the mixing container over their smaller counterparts, contrary to the size-segregation theory. Our findings may increase precision and predictability of particle movement of non-enclosed hollow objects among unrelated items. A better understanding of particle distribution that may explain certain phenomena (i.e., that larger particles tend to rise to the top of a mixture and not sink under the influence of gravity) could be useful for many fields that deal with particulate matter from geology to chemistry.

INTRODUCTION

The way that particles in an enclosed space organize themselves is the result of many principles of physics, such as gravity and friction. In the arrangement of particles, a strange pattern was noticed, known as the size-segregation quandary which has been debated among physicists for years (1–3). The quandary states that larger objects rise to the top of a mixture when mixed with smaller particles, independent of the implications of gravity (2). For a long time, many scientists believed that the answer lay in the micromechanical structure of the involved particles, including friction and energy displacement. (2) The cause of granular particle movement has been particularly evaluated (1), and theories about granular particulate movement have been compared and contrasted (4). The current explanation of size segregation revolves around the idea that smaller particles tend to be found at the bottom of mixtures and the larger ones at the top because smaller particles have a greater opportunity for downward mobility when the mixture is disturbed (3). The smaller particles gain this added mobility when the mixture is by falling through small and large openings while large particles can only fall through sufficiently large openings (5).

Hollow objects, however, were not considered in previous studies, and neither was density (6). Taking that a variety of particles are used in polymer formation and are studied in fields such as geology, it is key to understand the movement and interactions of non-uniform, possibly hollow objects within enclosed spaces (7). We proposed that hollow objects do not abide by the simple premise of the size-segregation theory that larger objects come to the top. Instead, we hypothesized that size, weight distribution, and circumference are responsible for the unusual behavior of the large objects. While the hollow beads may appear to be both larger at times and heavier, the former has some stipulations. The hollow bead, slightly cylindrical in nature, has two varying radii: one from top to middle and the other from side to middle, particularly in regard to the smaller side. Therefore, depending on the orientation of the bead during mixing, the perceived circumference could change slightly enough to change the order of the beads. Indeed, we found that circumference of the bead facing downward determined its vertical mobility to the bottom of the cup. Among misshapen, non-uniform objects, there appears to be a lack of predictability among particle arrangement, unless the particles are of a generally similar shape. Overall, the results of our study suggest that circumference, and resulting diameter, rather than size alone dictates the arrangement of falling objects. Beads fell according to a distinct pattern which when noted clarified and slightly modified the present size segregation theory regarding the behavior of non-uniform, specifically hollow particles within enclosed spaces.

RESULTS

To test the impact of factors outside of general size on vertical movement of objects within mixtures, we performed a falling bead experiment within a homogenous and heterogenous mixture of other beads **(Figure 1)**. Due to the different diameters of the different sides of the hollow beads, especially the fact that the small side has the longest diameter horizontally, the way the bead falls dictates its size and location in the cup **(Figure 1A-F', Y)**. With respect to themselves, all the beads exhibit gravitational influence. To test for the preferential effect of gravity on beads which have one length when turned one way and a different length when turned the other way, we placed spherical beads in an enclosed space (cup) with non-uniform hollow beads. Since

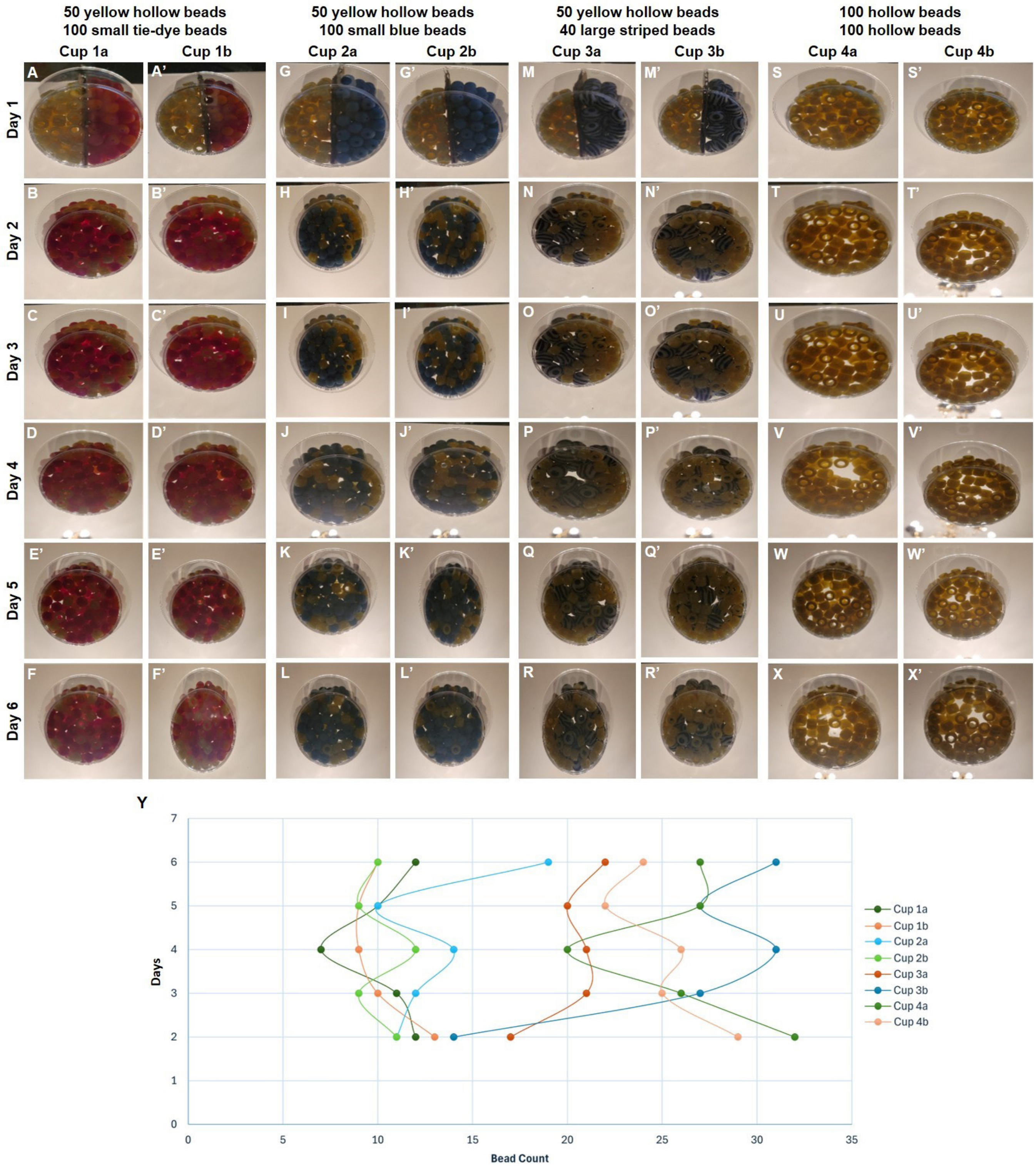

Figure 1: Visual display of beads in cups over time. (A-F') 50 yellow hollow beads and 100 small tie-dye beads are positioned in 2 cups (separated by partition) on a level surface (A-A'). (G-L') 50 yellow hollow beads and 100 small blue beads are positioned in 2 cups (separated by partition) on a level surface (G-G'). (M-R') 50 yellow hollow beads and 40 large striped beads are positioned in 2 cups (separated by partition) on a level surface (M-M'). (S-X') 100 hollow beads and 100 hollow beads are placed in cups on a level surface (S-S'). After partition removal, beads are stirred with the instrument (the eraser end of a pencil) once counterclockwise each day through day 6 touching the bottom of the cup (C-F', H-L', N-R', T-X'). Bead arrangement from the bottom of the cup is displayed in each cup and the number of hollow beads were documented at 6pm ET each day. Y) Line graph of data results (Days 2-6). The number of hollow beads recorded after stirring is shown on the X-axis and each cup per day is displayed on the Y-axis for Days 2-6. The trend generally increases for the number of hollow beads displayed each day per cup. Cups 1a-b (A-F'); Cups 2a-b (G-L'); Cups 3a-b (M-R'); Cups 4a-b (S-X').

https://doi.org/10.59720/21-182

gravity affects the orientation and the resulting layer of beads on the bottom, we recorded the number of beads of each type as well as their orientation (if hollow) to measure the effect of gravity on each respective bead. In our experiment, we mixed 50 yellow hollow beads with 100 small tie-dye beads and found that hollow beads, despite being bigger overall, fell with their smaller face downwards faster than the smaller beads **(Figure 1G-L')**. To control for specific beads that we used, we next mixed the same number of yellow hollow beads with 100 small blue beads and found similar results regarding the smaller side of the hollow beads being downwards facing and reaching the bottom faster than the overall smaller blue beads. To note the general trend of bead motion, bead movement was charted across six days of disturbance through stirring each day. The hollow beads were also intermingled with noticeably larger beads as well as with themselves and findings were consistent. Hollow beads with either the small or larger side facing downwards were more plentiful at the bottom compared to the larger beads **(Figure 1M-R')**. When mixed with themselves, hollow beads with the smaller side facing downwards were more plentiful at the bottom than the wider side facing downwards as expected **(Figure 1S-X')**.

DISCUSSION

Within our study, we utilized small, large, and hollow beads placed in different clear cups which were stirred, monitored, and photographed daily to observe and chart behavior. Our findings were quantified by counting the number and type of beads which were present at the bottom of the cups each day. When evenly mixed from a standard position within a controlled environment over the course of five days, beads with varying hollowness, weight, and size first begin to behave according to the accepted theory regarding size and segregation but gradually depart from the established theory with daily mixing. This details that another factor, perhaps circumference, affects bead movement as well.

A difference in arrangement between the hollow beads and the large beads was only noted because of the circumferential difference among the hollow beads with different shapes and density distributions. The charted results showed that the uniformity of circumference, particularly of the smaller beads as well as the large circumference of the large beads affects the arrangement initially, but gravitational pull affects the beads secondly. The fact that hollow beads trended downwards among the small beads and upwards among large beads reveals that circumference affects the fall foremost and gravity second. The fact, however, that the smaller side yellow beads remain at the bottom compared to their larger side among smaller beads, attests that uniformity of circumference is at play as well along with the gravitational pull. The effect of gravity overall pulls the beads downwards but the circumference of the downwards facing side dictates the rate of fall, especially in the presence of other beads. The small side of the hollow bead, despite its large diameter compared to the smaller beads, was viewed frequently at the bottom, which shows that it is still being influenced by its smaller circumference. Gravity helps determine the orientation while the size segregation theory dictates which beads travel to the bottom more readily because of at least one smaller circumference. Possible experimental errors that could have contributed to our results are the tendency of similar beads to gather together due to their surface texture minimizing friction. Additionally, any disturbance to the mixtures was highly minimized by experimenting in a secure location. Despite possible errors, some key findings emerged. Nevertheless, the results of our study are valuable as they show there are exceptions to a previously universal rule. To find further exceptions, one could experiment using large cubes and small beads, to see if the rectangular friction overwhelms the size-segregation principle.

Our findings take into account the possibility of varying circumferences of slightly oblong objects, or objects without a definite shape. Such could be applied to hollow polymer particles on the nanometer scale, whose behavior must be understood within an enclosed space. The size-segregation theory should take into account the circumferential effect on object segregation We additionally consider the influence of gravity in the downwards vertical movement of each kind of particle. The pull of gravity is a probable factor and seems to overwhelm the size-segregation theory when variables, such as the presence of objects with unidentical faces, are minimized. One example of such an interaction is demonstrated when hollow beads are allowed to migrate within an enclosed space. Some objects do not have a continuous shape, such that one face has a certain width and when turned another way has a different width. Those objects with varying circumferences based upon orientation will also be prone to a variability in movement in an enclosed space. This is thought to be due to the ability to fall when spaces larger than whichever side is facing downwards are available. Theoretically, such variances could be predicted using probability. Greater exploration of this phenomenon can be applied to the fields of biology, engineering, and manufacturing with respect to the novel hollow polymer particles (HPP) on the nanometer level (4). Such technology is being used as a cellular vector with "controllable holes" in order to increase the versatility of the size of the vector (1). Having a better understanding of such an issue could be of great scientific value as it can be applied to particle behavior.

MATERIALS AND METHODS

Within our study, we utilized small, large, and hollow beads placed in different clear cups which were stirred, monitored, and photographed daily to observe and chart behavior. Our findings were quantified by counting the number and type of beads which were present at the bottom of the cups each day. Plastic large (striped), two kinds of small (tie-dye and blue), and hollow beads (yellow) were used weighing: 1 gram, 0.0667 gram (both), and 0.25 grams, respectively. The hypothesis was tested by setting up eight identical clear cups and filling them with the following quantities of beads: 100 tie-dye small and 50 hollow, 100 blue small and 50 hollow, 40 large and 50 hollow, 100 hollow and 100 hollow. The diameter of each bead is as follows: 11mm (large), 7 mm (tie-dye and blue small), 7mm (large side hollow), 7mm and 8mm (small side hollow vertical and horizontal measurement). The number of hollow beads was counted on the bottom of each clear cup **(Figure 1)**. Upon setting up the experiment, I ascertained eight cups to demonstrate four scenarios of size segregation. Two cups contained beads of the following arrangement: hollow beads with one kind of small bead, hollow beads with another type of small bead, hollow beads with large beads, and lastly two cups with all hollow beads. I stirred the eight cups once a day for six days with their arrangements being photographed and noted each day.

If the hollow beads truly did have the potential to behave in erratic ways based solely on their possession of two circumferences, then the results when individually mixed with both small and large beads, would concur. The cups were put on a level and undisturbed surface to eliminate additional kinetic variables. On Day 1 **(Cup A and B)**, the cups were partitioned in the center while initially depositing the beads to both ensure separation of each kind of bead and to give each kind of bead a similar starting point and surface area on the bottom **(Figure 1)**.

When the partition was first removed as well as each day after stirring, the number and category of a specified kind of bead on the bottom of each transparent cup were recorded. The experiment lasted five days. Because the initial set was Day 1, data was captured Day 2 through Day 6. Each cup was stirred once counterclockwise, with the instrument (the eraser end of a pencil) touching the bottom of the cup. The cups were stirred, and the bead arrangement was documented by visually counting the number of beads at exactly 6:00pm ET each day. Only one stir was administered per day to simulate natural progression. Externally-derived commotion as well as natural settling of beads over a day's time was noted **(Figure 1)**.

Received: August 25, 2021
Accepted: September 25, 2023
Published: October 14, 2024

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