The Size-Weight Illusion Is Not an Illusion When Picking the Best Objects to Throw

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Heaviness perception involves a misperception of weight known, since the 19th century, as the Size-Weight Illusion[1]. The larger of two objects of equal mass is reported to be lighter than the smaller when they are lifted. The illusion has been found to be reliable and robust. It persists even when people know that the masses are equal and handle objects properly[2]. It has been exhibited by children of only 2 years of age[3,4]. All this suggests that the effect might be intrinsic to humans. Although different hypotheses have been advanced to account for the illusion over the 100+ years it has been studied[5-11], its origin remains unknown. More recently, people's perception of optimal objects for long distance throwing was found to exhibit a size-weight relation similar to the illusion[12,13], greater weights were picked for larger objects and they were indeed thrown to the greatest distances. Here we show that the perception of heaviness (including the illusion) and perception of optimal objects for long distance throwing are in fact equivalent. Thus, the size-weight illusion has a useful application: optimal objects for throwing are picked by a thrower as having a particular heaviness, which is the best heaviness learned when learning to throw[14,15]. Long distance throwing is a uniquely human ability that is understood to have enabled our species to survive and even thrive during the ice ages[16-22]. The fact that the illusion is a functional component of human throwing skill adds credence to the idea that it is intrinsic to the species.

Weight perception studies have sought to discover how relevant dimensions of a physical stimulus are scaled by the human perceptual system to produce experience of heaviness. Early studies quantified heaviness as a function of object weight[5]. However, in the 1890's, Charpentier[1] found that object size also affected perceived heaviness. A larger object is perceived to be substantially less heavy than a smaller one of equal weight. This phenomenon is known as the “size-weight illusion” and is by far the best known, most reliable and robust perceptual illusion.

Many theories have been advanced to account for the illusion in terms of either afferent or efferent processing. From the afferent point of view, the illusion merely reflects a complex sensory variable composed of size and weight. Different size-weight relations including density[6,7], a power-law[8], and an inertia tensor[9] have been proposed. In the efferent view, the illusion is a cognitive resolution of a conflict between planned and updated motor commands for lifting an object. According to this expectation hypothesis[10], a greater neuromuscular force is planned before lifting larger objects in response to visual and haptic size cues, and when the force actually required is less than expected, the object feels light. Because the expectation was assumed to come from average experience of larger objects as weighing more, the illusion was also considered to be modifiable by experience. Flanagan et al.[11] demonstrated that the illusion could be inverted after extensive training with objects in which size and weight were negatively correlated.

However, this experience-based hypothesis was undermined by other findings, some of which suggest that the illusion might be intrinsic to humans. The illusion is universally and reliably experienced by adults and children as young as 18 months[3,4]. The illusion is very robust. Knowing that two objects are of the same weight does not prevent the illusion from occurring. It has been found to persist after an object has been lifted and its weight thoroughly tested with the result that lifting trajectories are appropriate[2].

While the origin of the size-weight illusion remains controversial, the fact that it is so reliable and robust suggests that it might be in some way functional in the guiding of action. If so, then from the evidence, it is experiential and would have to do with judgments about objects made in planning actions rather than with continuous online control of actions. So, it might serve in the perception of affordances[*]. Here we investigated the possibility that the illusion specifies an affordance for long distance throwing.

Gibson[24] described affordances as dispositional properties that (1) reflect potential relations between an animal and objects used in performing actions and (2) are perceptible. The functional nature of affordances provides the means by which they are investigated and discovered. One investigates properties of objects that are relevant to specific actions. Then, the perceptibility of the property is assessed and finally, the information allowing an affordance to be perceived must be discovered.

An object of graspable size and liftable weight affords throwing. Bingham et al[12] investigated the perception of an affordance for throwing. In their study, spherical objects of different weights in a particular size were given to participants to judge the throwability, that is, the optimal weight for the size that could be thrown to a maximum distance. The task was intuitive and participants exhibited strong preferences in each of

[*] Note that the expectancy theory would seem to be about the planning of actions in a similar way, but instead, it is about how one perceives failures of such planning and the result is not described as serving any particular useful purpose.

four graspable sizes of objects. They hefted objects and selected larger weights in larger sizes. When they were asked to throw every object as far as they could, the preferred objects were reliably thrown to the farthest distances. This result was recently replicated by Zhu and Bingham[14].

Unsuccessful attempts have been made to discover the information that allows for detection of this affordance property[13,14]. Given that the ability to throw long distance must be learned, Zhu and Bingham[15] suspected that sensitivity to information about the affordance might be acquired in the process. The perception and throwing of unskilled throwers were tested before and after they practiced throwing for a month and perception of the affordance was found to be acquired only after learning to throw. To what information did throwers become sensitive to perceive the affordance? To answer this question, the learning experience of unskilled throwers was manipulated. Object sizes and weights experienced during practice were limited to three sets of six objects of constant size, constant weight, or constant density. If throwers associatively acquired either a look-up table or a function relating size and weight to distance, then practice with objects that limited the sampling should have limited subsequent perceptual ability to the objects experienced. However, the result was that the ability gained through practice generalized to the entire set of objects, that is, beyond the practice sets. This indicated that throwers acquired sensitivity to an information variable that specified the optimal size-weight relation. The practice sets were sufficient to allow this.

These results left an important question: what was the information detected and used to judge the affordance for throwing? Bingham et al[12] had noted that the size-weight relation for the affordance resembled that for the size-weight illusion, where larger objects must weigh more to be perceived as equally heavy. We now explicitly tested whether these two functions are the same. If so, then the solution to the question is simple. Throwers learn the heaviness of objects that is best for maximum distance throwing and then, they simply use that perceived heaviness to select objects that are best for throwing.

Insert Table 1 about here

Table 1 | The configuration of object weights and sizes

48 spherical objects that varied in size and weight as shown in Table 1 were used[14,15]. Twelve skilled adult throwers were recruited to perform two judgment tasks by hefting the objects as in previous studies. Participants were first asked to select optimal weights in each size for maximum distance throws. Then, they were asked to select an object in each size that was of the same heaviness as a comparison object. Two different comparison objects were tested of 1" and 6" size, respectively. Participants were randomly assigned to one of two groups that each tested small or large comparison objects, respectively. The comparison object judged by each participant in the heaviness task was the object (in the relevant size) selected by the same participant as optimal for throwing, but this was not known by the participants.

As shown in Figure 1, there was no significant difference between the two judgments (throwing versus heaviness) in either of the two groups (small or large comparison object), indicating that the objects selected to be optimal for throwing were also felt to be equally heavy ($F_{1,5} = 0.001$, $p > 0.05$). The chosen weights increased as objects increased in size ($F_{5, 25} = 84.92$, $p < 0.001$), reflecting the standard pattern of the size-weight illusion.

Insert Figure 1 about here

Figure 1 | The mean selected object weights for throwing judgments and heaviness judgments as a function of object sizes. The filled squares connected with a solid line represent the mean weights selected for long distance throwing in each respective size; the unfilled squares connected with a dashed line represent the mean weights selected as equal in heaviness across the respective sizes. The overlap of the two judgment lines indicates that the weights selected as optimal for throwing were also perceived to be equally heavy ($F_{1,5} = 0.001$, $p > 0.05$). Both judgments exhibited increasing weights with increasing sizes ($F_{5, 25} = 84.92$, $p < 0.001$), suggesting that both judgments were subject to the size-weight illusion.

This is quite a remarkable result. Illusions are by definition misperceptions associated with dysfunction. However, we have found that the most striking, robust and best known illusion in the literature is actually quite functional. More than this, it serves in support of an ability that is both uniquely human and known to have been essential to the survival and successes of our species over evolutionary time[16-20]. Other primates and monkeys can throw, but only to relatively short distances[25]. Today, human throwing abilities are used primarily in sport where we celebrate the long pass by the quarterback to hit a receiver 30 meters down the field in American football or the throw to home plate or wicket from the outfield in baseball or cricket. During most of our existence, however, we humans used our unique throwing abilities for defence and to obtain food. The ability to throw objects long distance is known to have been of central importance to the survival of homo sapiens through the last ice age, and to the spread of humans to occupy habitats all over the globe, and North America in particular, where homo sapiens used throwing ability to hunt the existing American megafauna into extinction[21-23]. The ability to throw long distance meant that a human hunter could stay beyond the devastating reach of a giant sloth's claws or a mammoth's tusks while striking with spears and stones to bring the prey down. Such throwing requires precise timing in motor coordination and this, in turn, is supported by the human cerebellum and posterior parietal structures in the brain[26]. A solution to a puzzle in human evolution has been recently proposed. The human ancestor with the larger brain was always the one to succeed and survive with the sole exception of Neanderthal, whose brain was actually larger than that of homo sapiens. Why did homo sapiens win out despite the smaller brain size? Evidence now reveals structural differences, namely, homo sapiens had relatively enlarged cerebellum and posterior parietal cortex as compared to Neanderthal[27]. Perhaps our throwing abilities were the key. The bottom line is that long distance throwing is an ability as essentially human as is language.

Now, we find that a characteristic of human visual and haptic perception, previously understood as a mis-function, is actually very useful. The perception of heaviness according to the size-weight illusion might well be intrinsic to human perception given its robust and reliable presence in people across the age span. Our results suggest that it represents a readiness in humans to acquire both the ability to throw long distance and to find objects that will maximize the distances to which one can throw.

Methods

With informed consent, adult throwers were recruited from the UW campus to judge optimal objects for throwing as well as object heaviness. Judgments were analyzed using repeated measures ANOVA with the significance level set at $p < 0.05$.

48 spherical objects were constructed with weights and sizes as shown in Table 1. These included three subsets: six objects of a constant weight (69 g) varying only in size; six objects of constant size (7.62 cm in diameter) varying only in weight; and six objects of constant density (0.3 g/cm^3) varying in both size and weight. Objects consisted of pure Styrofoam, steel shells, or plastic shells containing homogeneously

distributed sprung brass wire and foam insulation. All were wrapped with tape and painted yellow to yield identical surface texture and appearance.

Experiment design and procedure. 12 adult throwers were recruited from the University of Wyoming Laramie campus after they had given informed consent. They all could throw a tennis ball at least 20 meters. Participants performed two judgment tasks involving the entire set of 48 objects. They first performed a judgment of the optimal weight for each object size for maximum distance throwing. Then, they were randomly assigned to one of two groups to select objects of equal heaviness to a comparison object. The comparison objects were the objects selected for throwing by the participants in the smallest (Group 1) or largest (Group 2) sizes. This was unknown to the participants.

The experimenter placed 8 objects of a given size and varying in weight on a table. The participant held out his or her dominant hand palm up and the experimenter placed one object at a time in the participant's hand to be hefted briefly to feel its size and weight and judge its throwability. After hefting all 8 objects, the participant was asked to select by pointing the best 3 objects for throwing to a maximum distance in order from 1st to 3rd best. 6 different object sizes (ball diameter ranges from 1 inch to 6 inch) were tested in this way in a random order.

The same objects were used for the judgments of equal heaviness. Participants were first given the comparison object to heft. Next, participants were given all the objects in each of the other sizes (one size at a time and one object at a time) to heft, and they were asked to select the object that felt equally heavy as the comparison object. Again, they were asked to make a 1st, 2nd and 3rd choice. Different sizes were tested in a random order. For analysis of results, a weighted average of the 1st, 2nd, and 3rd choices was computed for each judgement type and participant.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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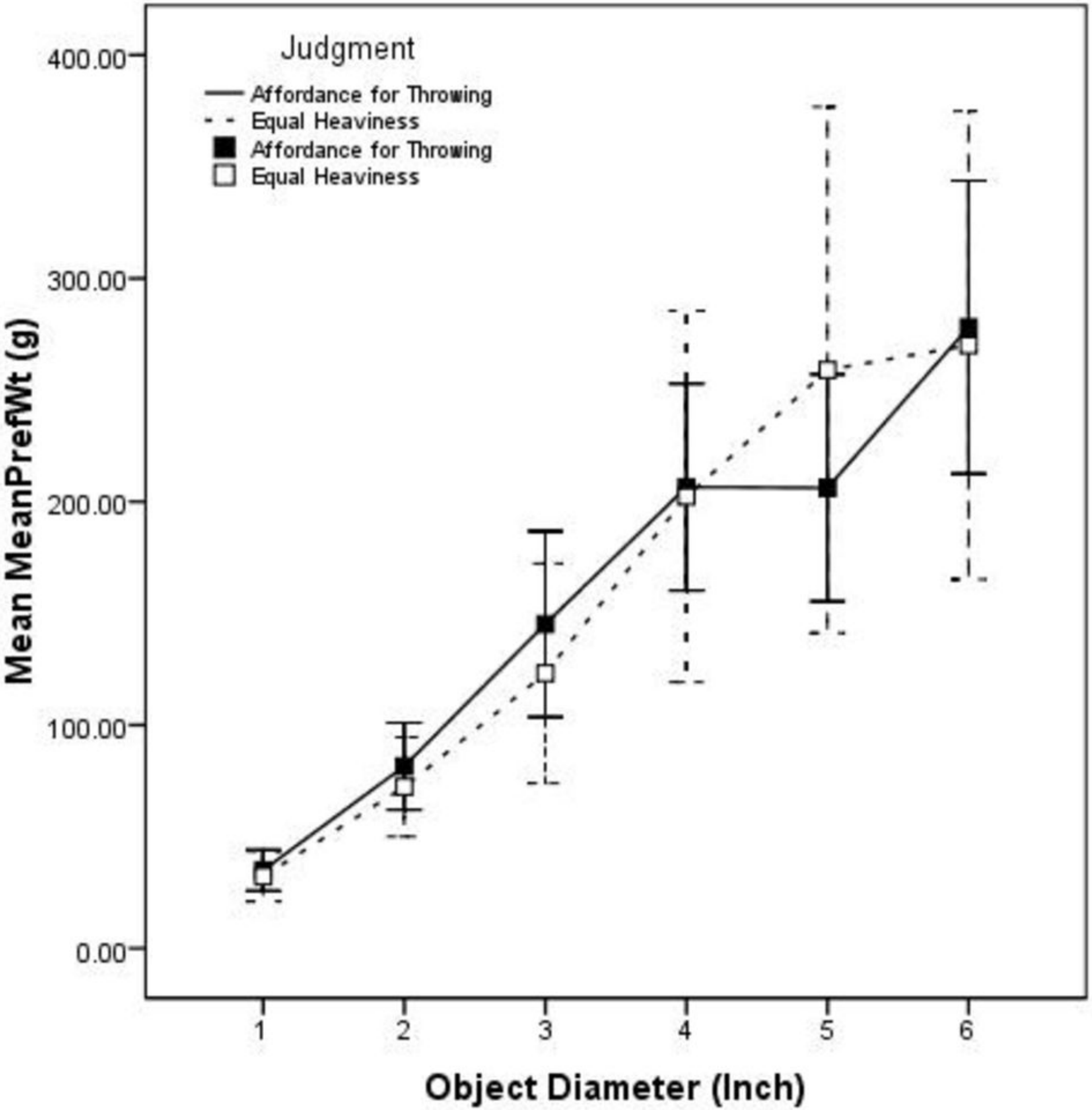
Judgment
Affordance for Throwing
Equal Heaviness
Affordance for Throwing
Equal Heaviness
400.00
300.00
200.00
100.00
0.00
Mean MeanPrefWt (g)
1
2
3
4
5
6
Object Diameter (Inch)

Object Configuration Table

Diameters(cm)	Object weight (g)							
1" / 2.54cm	3.2	5	7.7	11.9	18.5	28.6	44.4	**68.8**
2" / 5.08cm	7.7	11.9	18.5	28.7	44.4	**68.9**	106.8	165.5
3" / 7.62cm	18.5	*28.7*	*44.4*	***68.9***	*107*	*166*	*257*	397.6
4" /10.16cm	29	45	**69.7**	108	167.4	259.5	402.2	623.3
5" /12.70cm	45	**69.8**	108.1	167.6	259.7	402.6	624	967.2
6" /15.24cm	**69**	107	165.8	256.9	398.3	617.3	956.8	1483.1

NOTE: **BOLD** figures denotes the Constant Weight subset
ITALIC figures denotes the Constant Size subset
UNDERSCORED figures denote the Constant Density subset