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Human readiness to throw: the size–weight illusion is not an illusion when picking the best objects to throw[☆]

Qin Zhu[a,]*, Geoffrey P. Bingham[b]

[a]*Division of Kinesiology and Health, University of Wyoming, Laramie, WY 82070, USA*
[b]*Department of Psychological and Brain Sciences, Indiana University, Bloomington, IN 47405, USA*

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Abstract

Long-distance throwing is uniquely human and enabled *Homo sapiens* to survive and even thrive during the ice ages. The precise motoric timing required relates throwing and speech abilities as dependent on the same uniquely human brain structures. Evidence from studies of brain evolution is consistent with this understanding of the evolution and success of *H. sapiens*. Recent theories of language development find readiness to develop language capabilities in perceptual biases that help generate ability to detect relevant higher order acoustic units that underlie speech. Might human throwing capabilities exhibit similar forms of readiness? Recently, human perception of optimal objects for long-distance throwing was found to exhibit a size–weight relation similar to the size–weight illusion; greater weights were picked for larger objects and were thrown the farthest. The size–weight illusion is: lift two objects of equal mass but different size, the larger is misperceived to be less heavy than the smaller. The illusion is reliable and robust. It persists when people know the masses are equal and handle objects properly. Children less than 2 years of age exhibit it. These findings suggest the illusion is intrinsic to humans. Here we show that perception of heaviness (including the illusion) and perception of optimal objects for throwing are equivalent. Thus, the illusion is functional, not a misperception: optimal objects for throwing are picked as having a particular heaviness. The best heaviness is learned while acquiring throwing skill. We suggest that the illusion is a perceptual bias that reflects readiness to acquire fully functional throwing ability. This unites human throwing and speaking abilities in development in a manner that is consistent with the evolutionary history.

Keywords: Size–weight illusion; Overarm throwing; Language; Human evolution

1. Introduction

Long-distance (≈20–30 m) throwing is an ability that is both uniquely human and known to have been essential to the survival and successes of *Homo sapiens* over evolutionary time (e.g. Bingham, 1999; Calvin, 1983; Darlington, 1975; Isaac, 1987; Knusel, 1992; Martin, 2005; Meltzer, 2009; Shea, 2006). Other primates and monkeys can throw, but only to relatively short distances (Cleveland, Rocca, Wendt & Westergaard, 2003). Today, human throwing abilities are used primarily in sport where we celebrate the long pass by the quarterback to hit a receiver 30 yards 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 humans through the last ice age and to the spread of humans to occupy habitats all over the globe, and North America in particular, where *H. sapiens* used throwing ability to hunt the existing American megafauna and contribute to its extinction (Bingham, 1999; Martin, 2005; Meltzer, 2009; Finlayson, 2009; Flannery, 2001). 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 (Meltzer, 2009). Also, when global temperature dropped and

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* Corresponding author.
E-mail address: qzhu1@uwyo.edu (Q. Zhu).

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forested regions became de-forested steppe tundra, a hunter could no longer hide well to ambush its prey from short distance. The ability to throw to take down prey at long distance became crucial for survival (Finlayson, 2009).

Long-distance throwing requires precise timing in motor coordination (e.g., Jöris, van Muyen, van Ingen Schenau & Kemper, 1985), and this, in turn, is supported by the cerebellum and posterior parietal structures in the brain of *H. sapiens* (Ivry & Spencer, 2004; Ivry, 1997). There has been a puzzle in the understanding of the evolution of the human brain. These structures are featured in a recently proposed solution to the puzzle. The proto-human species with the larger brain was always the one to succeed and survive, with the sole exception of Neanderthals, whose brain was actually larger than that of *H. sapiens*. Why did *H. sapiens* win out despite the smaller brain size? Evidence now reveals structural differences, namely, *H. sapiens* had relatively enlarged cerebellum and posterior parietal cortex as compared to Neanderthals (Weaver, 2005). Concurrent discussions have suggested that, indeed, throwing ability was key to the survival of *H. sapiens* in contrast to Neanderthals (Finlayson, 2009).

Long-distance throwing is an ability that is as essentially human as is language (Bingham, 1999; Calvin, 1983). The motoric timing required for speech is similar in its requisite precision to that for throwing and is similarly supported by relevant brain structures (Mathiak, Hertrich, Grodd & Ackermann, 2002; Ackermann & Hertrich, 2000; Calvin, 1993; Keller, 1990; Ivry & Spencer, 2004). Speech is understood to have been essential to allow socially coordinated throwing in hunting of large game, so throwing and speech are coupled in having made humans uniquely successful (Bingham, 1999; Calvin, 1983; Finlayson, 2009; Flannery, 2001; Martin, 2005; Meltzer, 2009). Speech has been widely appreciated as intrinsic to humans, something very young humans exhibit readiness to learn with rapidity (Kuhl, 2000; Kuhl, Conboy, Padden, Nelson & Pruitt, 2005; Kuhl & Rivera-Gaviola, 2008; Lenneberg, 1967). What of throwing in this regard? We now present a result that supports the possibility that throwing is similarly intrinsic by showing that it is related to a long and well-known phenomenon in human haptic perception of graspable objects, namely, the size–weight illusion. Our finding reveals that this illusion represents a readiness in humans to acquire fully functional throwing abilities.

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 (Weber, 1834/1978). However, Charpentier (1891) 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 among the best known, most reliable and robust perceptual illusions.

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 (Huang, 1945; Ross & DiLollo, 1970), a power law (Stevens & Rubin, 1970) and an inertia tensor (Amazeen & Turvey, 1996) have been proposed. The scaling of size and weight to heaviness as described by the power law, for instance, has not been found to support the hypothesis that it is really density that is being perceived, but the real meaning of the property captured by the power law remains unclear. The inertia tensor hypothesis was originally tested by having participants wield specially weighted rods. More recently, the hypothesis was tested using weighted balls that were grasped and hefted, that is, the standard circumstance in which the illusion is experienced (Zhu, Shockley, Riley & Bingham, submitted for publication). The results failed to support the inertia tensor hypothesis.

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 (Ross, 1966), 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 and Beltzner (2000) demonstrated that the illusion could be inverted after extensive training with objects in which size and weight were negatively correlated. More recently, Brayanov and Smith (2010) found that perceptual judgments and motoric responses in object handling were different in respect to the illusion. They reported that perceptual judgments were less affected by prior experience than motoric responses were.

The experience-based hypothesis has been 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 (Robinson, 1964; Kloos & Amazeen, 2002). 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 (Mon-Williams & Murray, 2000).

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.[1] Here we investigated the possibility that the illusion specifies an affordance for long-distance throwing.

To be able to plan their actions, animals must be able to see what the environment affords for possible future actions. Gibson (1986) described affordances as perceptible dispositional properties that reflect potential relations between an animal and objects used in performing actions. Examples are the graspability of a coffee cup (Mon-William & Bingham, in press), the sitability of a chair (Mark, 1987), the climbability of a stairway (Warren, 1984) or the passability of a doorway (Warren & Whang, 1987). 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 (for instance, passability is determined by the width of a doorway relative to the width of the shoulders of a person walking through the doorway plus a safe margin for passage ≈30%). Then, the perceptibility of the property is assessed and, finally, the information allowing an affordance to be perceived must be discovered [see for instance eye-height scaled visual information found by Warren and Whang (1987) for perception of the passability of a doorway].

An object of graspable size and liftable weight affords throwing. Bingham, Schmidt and Rosenblum (1989) 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 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 (2008).

Unsuccessful attempts have been made to discover the information that allows for detection of this affordance property (Zhu & Bingham, 2008; 2009). Given that the ability to throw long distance must be learned, Zhu and Bingham (2010) tested the hypothesis 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. (1989) 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.

2. Methods

2.1. Participants

Twelve adult throwers were recruited from the University of Wyoming Laramie campus after they had given informed consent. Half were male and half female. The mean age was 24.6 years. They all could throw a tennis ball at least 20 m.

2.2. Experimental objects

Forty-eight 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.

Table 1

Diameter (cm)	Object weight (g)							
2.54	$\underline{3.2}$	5	7.7	11.9	18.5	28.6	44.4	**68.8**
5.08	7.7	11.9	$\underline{18.5}$	28.7	44.4	**68.9**	106.8	165.5
7.62	18.5	*28.7*	*44.4*	***$\underline{68.9}$***	*107*	*166*	*257*	397.6
10.16	29	45	**69.7**	108	$\underline{167.4}$	259.5	402.2	623.3
12.70	45	**69.8**	108.1	167.6	259.7	$\underline{402.6}$	624	967.2
15.24	**69**	107	165.8	256.9	398.3	$\underline{617.3}$	956.8	1483

Bold figures denote the constant weight subset; italicized figures denote the constant size subset; underlined figures denote the constant density subset.

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[1] 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 after the fact and the result is not described as serving any particular useful purpose.

2.3. Experiment design and procedure

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. Eight objects of a given size but varying in weight were placed on a table. The participant held out his or her dominant hand with palm up and the experimenter placed one object at a time in the participant's hand, asking the participant to feel its size and weight by hefting and then judge its throwability. After hefting all eight objects, the participant was asked to select by pointing the best three objects for throwing to a maximum distance in order from first to third best. Six different object sizes (ball diameter ranges from 1 to 6 in.) were tested in this way in a random order.

Then, participants were randomly assigned to one of two groups to select objects of equal heaviness to a comparison object. The objects used for the judgments of equal heaviness were the same as those used for judgments of throwability. Participants were first given the comparison object to heft. The comparison objects were the objects selected for throwing by the participants either in the smallest or in the largest sizes. Group 1 used the selected object in the smallest size as the comparison object and Group 2 used the selected object in the largest size. However, this was unknown to the participants. 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 first, second and third choice. Different sizes were tested in a random order.

3. Results

The three choices made by each participant were weighted to yield a mean preferred weight by multiplying the weight of the first chosen object by 0.5, of the second chosen object by 0.33 and of the third by 0.17, and then summing them up. The calculated mean preferred weights for all participants were plotted against the object size separately for each judgment task, throwability and heaviness. As seen in Fig. 1, the two lines representing the two judgments overlapped and they both increased as objects became larger, indicating that the objects selected to be optimal for throwing were also felt to be equally heavy despite the weights actually increasing with size.

A mixed-design ANOVA was performed on those calculated mean preferred weights treating group as a between-subject variable, and both judgment task and object size as within-subject variables.[2] The results showed no difference ($F_{1,10}=0.001$, $p>.9$) between the two judgments (throwing vs. heaviness) and no difference ($F_{1,10}=0.7$, $p>.4$) between the groups (small or large comparison object). The chosen weights increased as objects increased in size ($F_{5,50}=33.6$, $p<.001$), reflecting the standard pattern of the size–weight illusion. None of the interactions was significant (the p values were all >.25).

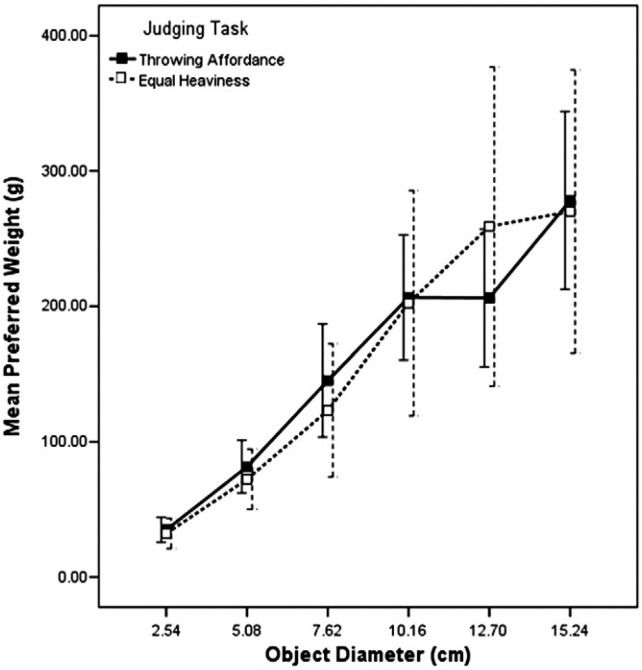

Fig. 1. Mean selected object weights for throwing judgments and heaviness judgments as a function of object sizes. The filled squares connected with a solid line represent the mean weights selected for long-distance throwing in each respective size; the unfilled squares connected with a dashed line represent the mean weights selected as equal in heaviness across the respective sizes.

Next, we regressed log preferred weights (that is, the log weighted mean for each size) for throwing judgments on those for heaviness judgments separately for each participant. Then, we computed the mean results across participants. Mean slope was .99 (standard error=0.07). Mean intercept was −0.03 (standard error=0.15). Mean r^2 was 0.90 (standard error=0.03). Thus, essentially the relation was slope=1 and intercept=0, meaning the two types of judgment were the same. The r^2 showed that these were good fits.

4. Discussion

This is quite a remarkable result. Illusions are by definition misperceptions associated with dysfunction. However, we have found that one of the most striking, robust and best known illusions in the literature is actually quite functional, serving in support of the human ability to throw long distance. The perception of heaviness, including the size–weight illusion, might be expected to be intrinsic to

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[2] Note, for these analyses, the results were the same when performed with either mean preferred weights or log mean preferred weights. The latter would be relevant because the weights in each size were generated as a geometric series. Also, half of the participants were male and half female, but we found no gender differences in the judgments.

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.

Throwing and language capabilities combined to enable humans to survive the challenges of rapid climatic and environmental change and to spread into habitats around the globe and to become the dominant large-scale (e.g., excluding insects) species on the planet. Speech and language are well understood to be intrinsic to humans, but what this means for the development of language ability in the individual has been itself changing in recent understanding. (See Kuhl (2000) for review of what follows.) Chomsky (1959) suggested that language was innate and in the form of a universal grammar that acted to select appropriate acoustic input that then automatically triggered the formation of specific language ability. More recently, however, readiness to acquire language has been understood to be less preformed and automatic, but instead to consist of biases in perception that contribute to spontaneous development of sensitivity to relevant higher order acoustic units underlying speech. “What is innate regarding language is not universal grammar and phonetics, but innate biases and strategies that place constraints on perception and learning” (Kuhl, 2000, p. 11,856). Kuhl has suggested in her Native Language Magnet Model that human infant acoustic perception warps the acoustic dimensions underlying speech to make more salient relevant acoustic differences and produce, over a dynamic developmental process, an ability to detect higher order (phonetic) units. Given the overlap in neurological structure supporting both speech and throwing capabilities together with their coordinated roles in successful human evolution, one might expect that throwing abilities would similarly exhibit some form of readiness in individual human development, correspondingly in the form of perceptual biases. Here we provide evidence of exactly this.

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