Is Hefting to Perceive the Affordance for Throwing a Smart Perceptual Mechanism?

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G. P. Bingham, R. C. Schmidt, and L. D. Rosenblum (1989) found that, by hefting objects of different sizes and weights, people could choose the optimal weight in each size for throwing to a maximum distance. In Experiment 1, the authors replicated this result. G. P. Bingham et al. hypothesized that hefting is a smart mechanism that allows objects to be perceived in the context of throwing dynamics. This hypothesis entails 2 assumptions. First, hefting by hand is required for information about throwing by hand. The authors tested and confirmed this in Experiments 2 and 3. Second, optimal objects are determined by the dynamics of throwing. In Experiment 4, the authors tested this by measuring throwing release angles and using them with mean thrown distances from Experiment 1 and object sizes and weights to simulate projectile motion and recover release velocities. The results showed that only weight, not size, affects throwing. This failed to provide evidence supporting the particular smart mechanism hypothesis of G. P. Bingham et al. Because the affordance relation is determined in part by the dynamics of projectile motion, the results imply that the affordance is learned from knowledge of results of throwing.

Keywords: afffordances, smart mechanism, haptic perception, dynamics, perceptual learning

Homo sapiens are unique in their ability to throw objects to significant distances (Young, 2003).[1] This ability is known to have been of central importance to the evolution and survival of the species through the ice ages to the current time (P. M. Bingham, 1999; Darlington, 1975; Isaac, 1987; Young, 2003). Human throwing ability is also unique in the relative complexity of the action and in the exquisite relative timing that is required (Hore, Ritchie, & Watts, 1999; Hore, Watts, Martin, & Miller, 1995; Joris, van Muyen, van Ingen Schenau, & Kemper, 1985). The energy of a throw is developed in the slower motions of the more massive trunk of the body and then is passed sequentially to less massful limb segments that move at proportionally faster speeds (e.g., Joris et al., 1985) yielding finally high-peak speed of the hand at the precisely timed moment of release (Hore et al., 1995, 1999). Specific brain structure and, in particular, the cerebellar structure and organization is known to be required for such precise relative timing of movements (Ivry, 1997; McNaughton, Timmann, Watts, & Hore, 2004). It has been hypothesized that the evolution of much of this brain structure and organization was specifically to support this adaptively advantageous behavior (Calvin, 1982, 1983a, 1983b; Stout & Chaminade, 2006; Stout, Toth, & Schick, 2007; Weaver, 2007). Recently, it has been found that increases in brain size exhibited by *Homo sapiens* compared with earlier spe-

cies entailed increases in cerebellum size specifically and, furthermore, that the difference between *Homo sapiens* and Neanderthals was that although Neanderthals actually had a larger brain than *Homo sapiens*, the cerebellum was smaller (Stout & Chaminade, 2006; Stout et al., 2007; Weaver, 2007). One inference is that *Homo sapiens* won out because they were better at throwing.

As the research reported in this article shows, human throwing ability is accompanied by the ability to perceive the affordance of objects for throwing and, in particular, for maximum distance throwing. This affordance and its perception are particularly interesting and important for reasons beyond the relevance to human evolution. As we show, the affordance consists of a continuous functional relation between object size and weight. This relation determines objects that can be thrown to a maximum distance: For any given graspable size, there is a weight that yields maximum distance throws. This affordance is unique among affordance properties studied to date for two reasons. First, it is intrinsically dynamic, both because it is mass related and because it entails the dynamics of throwing and of projectile motion. Second, the affordance is more complex than any studied to date. It entails a continuous single valued function of two variables: Maximum thrown distance is a function of both object size and weight.

This functional relation is notable because it happens to be the same as that corresponding to the classic size–weight illusion (G. P. Bingham et al., 1989). This illusion has attracted much attention because it is among the most salient and robust in the literature of perceptual illusions. The illusion is a misperception of

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[1] Monkeys and primates are able to throw accurately to hit targets at short ($\approx$ 1 m) distances, but only humans are able to throw to long (>30 m) distances (Westergaard, Liv, Haynie, & Suomi, 2000; Westergaard & Suomi, 1994).

weight. Given two objects of different size, the larger object must weigh more to be perceived of equal weight to the smaller object. The function corresponding to equal perceived weights of different sized objects also describes the optimal weights and sizes for maximum distance throwing. But in the latter case, the affordance property is correctly and accurately perceived. Both the robustness of the illusion and the accuracy of the affordance perception suggest that these related phenomena provide a window on a fundamental human perceptual capability.

The complexity of the functional relation corresponding to the affordance is challenging because the perception of the affordance must be learned. Only humans can really throw, but not all humans can throw well. Throwing is a skill that is learned and so presumably is the accompanying affordance. Function learning is an active area of research in psychology (DeLosh, Busemeyer & McDaniel, 1997; McDaniel & Busemeyer, 2005), but research efforts have only thus far addressed functions that map a single variable to another. The learning of a functional relation that maps two variables to a third is a special challenge in the understanding of function learning. In these studies, we investigated how the affordance might be perceived. However, the hypothesis we investigated was directly relevant to the means by which people might learn to perceive the affordance for maximal-distance throwing. We investigated the hypothesis that optimal objects for throwing are perceived via a particular smart perceptual mechanism, namely, the one hypothesized by G. P. Bingham et al. (1989). If this hypothesis were correct, then the requisite perceptual learning would be simpler. We explain this below.

The original investigation of this affordance by G. P. Bingham et al. (1989) was inspired by a common childhood competition at the beach. The game is to throw stones to see who can achieve the farthest distance out on the water. Part of the game is to select among stones on the beach those that are optimal for being thrown to a maximum distance. Assuming a roughly spherical shape, stones are selected depending on their relative size and weight. Stones usually exhibit nearly constant density, so size and weight covary. This means the problem can be solved by merely picking the best weight. If G. P. Bingham et al.'s smart mechanism hypothesis was found to be correct, this experience would be enough for throwers subsequently to be able to pick the optimal weight for any size object. If the hypothesis was found to be wrong, then experience of throwing with more extensive variations of sizes and weights should be required to learn to perceive the affordance.

The affordance involves object weight. Weight is a mass-dimensioned dynamic property. The majority of affordance studies have investigated the use of vision to perceive affordances (e.g., G. P. Bingham & Muchisky, 1993, 1993a, 1993b; Mark, 1987; Mark, Balliett, Craver, Douglas, & Fox, 1990; Warren, 1984; Warren & Whang, 1987), for instance, the visual perception of maximum seat height (Mark et al., 1990), of the maximum passable aperture (Warren & Whang, 1987), or of maximum climbable stair height (Warren, 1984). Exceptions are studies of dynamic touch (for a review, see Turvey, 1996) where, for instance, observers have been shown to be able to perceive, by wielding (without vision), the distance reachable by a handheld rod. Nevertheless, all these affordance properties are essentially geometric. Stair height, seat height, aperture width, and rod length are all length-dimensioned properties. The perception by hefting of opti-

mal throwing objects is different from these previously studied affordance properties because optimal throwability is inherently dynamic.[2]

The optimality of thrown objects is determined by the dynamics of throwing and the dynamics of projectile motion. Thus, these dynamics must be confronted to understand the affordance. The variables that determine the distance of travel in the dynamics of projectile motion are size (i.e., cross-sectional area) and weight of the projectile as well as the initial speed and angle at release (Parker, 1977). However, given a particular release angle and velocity for an object of a given size, variation of the weight does not yield an optimum distance from projectile motion dynamics. The distance of travel only increases with an increase in weight. It does not decrease. So, the determination of a weight for a given size that yields a maximum thrown distance necessarily entails the dynamics of throwing.

G. P. Bingham et al. (1989) reviewed studies of the dynamics of throwing and found that throwing has two essential aspects. First, as already mentioned, energy is developed starting with more massful proximal body segments and then is passed in sequence from one segment to the next proceeding distally from the trunk to the hand. Second, during the final stage of a throw (i.e., the last ≈ 100 ms), the object actually stops moving for an instant as the wrist is cocked injecting energy into the long tendons of the wrist by stretching them. This allows those tendons to amplify the energy by returning it at higher shortening velocity as the elbow and wrist extend and flex, respectively, to launch the object. G. P. Bingham et al. hypothesized that larger objects affected throwing by changing the length and, thus, the stiffness of the wrist tendons. The reason is that the same tendons contribute to the control of finger flexion in grasping and wrist flexion in throwing. Grasping larger objects shortens the tendons at the wrist yielding stiffer tendons (because of their curvilinear length–tension relation). G. P. Bingham et al. performed an experiment to measure the effect of grasped object size on stiffness at the wrist and found increases in stiffness with increasing object size as expected. Accordingly, they hypothesized that greater mass is required for larger objects both to preserve the frequency of the motion and to load the spring so as to yield high shortening velocity. The frequency of motion at the wrist would be preserved to preserve the relative time among the joints (shoulder, elbow, and wrist).

If optimal throwability is determined by the dynamics of throwing, how can hefting provide information about this affordance, that is, how can hefting provide information about an object's effect on throwing? One obvious hypothesis would be that past experience of throwing yields knowledge of the functional relation between object size and weight that yields maximum distance throws. Each time an object is thrown with a maximum effort, the distance of travel is noted (i.e., knowledge of results) and stored in memory together with the object size and weight. Eventually, after

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[2] Strictly speaking, dynamics is relevant to all of these affordances. The dynamics of walking is relevant to the size of passable apertures as is the dynamics of stair climbing to the size of the maximum climbable stair. Nevertheless, geometric properties were featured in the respective studies because they capture most of the variance. In the context of throwing, the dynamics must be addressed to formulate any understanding of the problem.

experience of sufficient variation in sizes and weights, this information is used to induce the function specifying optimal objects (DeLosh et al., 1997; McDaniel & Busemeyer, 2005). Because a different weight is optimal for each size, this function learning approach would require that the full range of throwable sizes and weights is each sampled adequately and independently. That is, optimal weights would have to be discovered for multiple sizes to induce the full functional relation.

There are two related problems with this idea. First, this entails the assumption that distances of throws can be accurately perceived and compared across occasions occurring in different environments and separated by significant amounts of time. Studies of distance perception have shown that absolute distances in the relevant range (up to 35 or 40 m) are not perceived accurately (Todd, Tittle, & Norman, 1995). Distances are even less accurately compared when perceived over ground surfaces composed of different textures, that is, throws performed over water versus a grass-covered field versus a sand- or gravel-covered beach (Hu, Gooch, Creem-Regehr, & Thompson, 2002). This need to compare across occasions in different environments at widely different times is introduced by a second assumption, already mentioned, which is that one would require experience of throwing a variety of different weights in each of different sizes. The size and weight would have to vary independently in throwing experience so that the optimal weight could be discovered in given sizes. The problem is that size and weight would covary in most contexts, for instance, heavier stones on the beach are simply the bigger ones. The same is true of apples in an orchard or wooden sticks in a forest or wads of paper in a classroom or rubber balls on a playground. Rarely would objects of different materials but similar size be encountered on a single occasion in a given context. Rather, baseball-sized stones would be encountered on the beach, whereas baseball-sized apples would be encountered in an orchard and actual baseballs would be encountered on the playing field. So, throws with objects of common size but different weight would typically be compared across occasions occurring in different environments at distant times. Given these two connected problems, what is the likelihood that optimal weights in arbitrary sizes could be discovered through experience? Where would one get the experience that would allow one to pick the optimal weights for balls across the full range of graspable ball sizes?

A second hypothesis as to how hefting can provide information about optimal objects for throwing was that hefting acts as a kind of smart perceptual mechanism (G. P. Bingham et al., 1989; Runeson, 1977). Runeson (1977) suggested that perception might be smart by taking advantage of particular circumstances in a task that simplify the perceptual problems. G. P. Bingham et al.'s (1989) application of the smart mechanism idea was that the dynamics of hefting should be similar to the dynamics of throwing. This would be the "smartness" that would allow hefting to provide a window on the effect of object size and weight on throwing. G. P. Bingham et al. suggested that hefting would allow participants to detect the effect of object size on wrist stiffness and to find the optimal weight given that stiffness. The role of past experience in this case would be to enable throwers (a) to develop good throwing skills and (b) to develop good sensitivity to the information provided by hefting about throwing. Specific experience of a variety of weights in each of a number of different sizes would not be required as it would be to learn the affordance using function

learning through knowledge of results. Rather, acquiring the smart mechanism would only require that one become sensitive to the information provided by the smart mechanism. This, in turn, should only require experience of different weights in a single size or, more likely in natural settings, experience of a single constant density series of objects of covarying sizes and weights. Once one learns to pick the optimal stone on the beach, for instance, one should be able to pick the optimal weight for objects of any given size (and density) within the throwable range.

The smart mechanism hypothesis entails two assumptions that we tested in the studies reported in this article. The first assumption was that hefting by hand would be required to provide specific information about throwing using the hand. The dynamics of throwing by hand is specific to the structure of the arm and hand. Seeing the object size and feeling the weight using the elbow or the foot would not be sufficient for predicting the hand throwing performance according to the smart mechanism hypothesis. The specific dynamics of hefting by hand would be required because it is similar to the dynamics of throwing by hand. We tested this assumption in Experiments 2 and 3.

The second assumption entailed by the smart mechanism hypothesis was that the optimal objects are uniquely determined by the dynamics of throwing and not that of projectile motion. We tested this in Experiment 4. First, however, we attempted in Experiment 1 to replicate the results of the hefting and throwing study done by G. P. Bingham et al. (1989).

Experiment 1: Hefting by Hand for Overhand Throwing

The first experiment was performed to replicate the original study. G. P. Bingham et al. (1989) tested spherical objects of 4 different sizes (from 5 cm to 12.5 cm in diameter) and of 8 different weights in each size (ranging from a 4 g to 700 g). Eight participants hefted the objects and selected preferred weights for throwing in each of the 4 sizes. A week after they performed this judgment task, 3 of the participants threw each of the 20 objects to a maximum distance 3 times (the objects were marked with a code that did not allow participants to identify the ones they had previously chosen, except perhaps as they had before, by hefting them). The result was that participants threw the preferred objects in each size to the farthest distance. In each size, as weights became progressively greater or less than the preferred weight, the thrown distance became progressively less, that is, mean distances exhibited an inverted U-shaped curve with preferred weights at the peak. The preferred weights varied with the size of the objects. Greater weight was preferred for larger sizes.

This original study only tested objects in four different sizes and only five of eight weights hefted were actually thrown. We now tested six different sizes spanning the range of graspable objects: 1 in., 2 in., 3 in., 4 in., 5 in., and 6 in. (i.e., from 2.5 cm to 15 cm in diameter). Also, now all objects were thrown. G. P. Bingham et al. (1989) only tested throwing for 3 of the 8 participants who did the hefting. We now tested 10 participants in both hefting and throwing.

The experiment involved two sessions, each separated by about a week. In the first session, participants were asked to heft balls and to select those they could throw to the farthest distance. They hefted a series of balls of a given size that varied in weight and chose the optimal weight in the size. In the second session,

participants were asked to throw each of the balls to a maximum distance. This was done in an open field outdoors.

The original study showed that an optimum weight for each size was successfully perceived and selected for throwing to a maximum distance, and the preferred weight increased with the size of object.

Method

Apparatus. A set of 47 spherical objects was made to vary in size and weight. Objects varied in size with diameters as follows: .025 m (1 in.), .050 m (2 in.), .076 m (3 in.), .102 m (4 in.), .127 m (5 in.), .152 m (6 in.). These sizes correspond roughly to a large marble, a golf ball, a racquetball, a baseball, a softball, and a small playground ball, respectively. Weights in each size varied according to a geometric progression, where n refers to an item in the series: $W_{n+1} = W_n \times 1.55$. Eight weights were generated in each of the five smaller sizes and seven in the largest size, starting each series with the lightest weight that could be constructed (see Table 1). Spherical shells in five of the sizes were available commercially. They were designed to float in water to insulate swimming pools. They consisted of a hard, durable hollow plastic shell. We manufactured like balls in the otherwise unavailable .127-m size. To do this, a .127-m diameter spherical steel mold was cut in half with hinges on each hemisphere for future closure, and then a fiberglass resin composite was put inside of the mold together with a balloon that was inflated to push the resin against the mold, which was then heated to form the desired sphere. For some of the heaviest balls at both the .025-m size and the .152-m size, we used commercially available solid steel balls instead of plastic shells. Finally, some of the lightest balls were pure Styrofoam, such as the ball at the .127-m size with a weight of .048 kg and the ball at the .152-m size with a weight of .100 kg. All balls were tested to be durable enough to withstand impacts from maximum distance throws. The surface of each ball was covered with a wrapping of thin, stretchable white tape to produce identical appearance and surface texture, good graspability, and improved durability.

To manipulate the weights, most of the balls were filled with a sprung brass wire that was injected into the ball through a small hole and which then spontaneously distributed itself homogeneously throughout the available interior perimeter of the shell. After this, foam insulation (a silica gel) was injected through the hole to fill the remaining space and rigidly stabilize the material inside the ball. For the extremely heavy weights, lead shot was projected into the sphere together with the foam insulation to mix

with the brass wires so as to achieve the desired weights with a homogeneous distribution of the interior mass.

The matrix of objects was designed to cover the range of throwable sizes and weights. The possible weights in the different sizes were constrained by the available materials for making the objects and the physical requirements for durability in the context of the throwing. The lightest objects in each size were pure Styrofoam, and the heaviest objects were essentially solid steel. A 100-m measuring tape was used to measure throwing distances.

Participants. Ten Indiana University undergraduates from the Department of Psychology were paid at a rate of $8 per hour for participation in each of the two sessions of the experiment. Half of the participants were men, and half of them were women. Participants were required to be capable of throwing objects and to have had some prior experience and skill at overarm throwing, to have good (corrected) vision, and to be free of motor impairments.

Experimental procedure. Participants were informed during recruitment that the experiment would consist of two sessions: one was hefting and judgment of the objects, lasting for about 45 min, and the other was throwing the objects across an outdoor field, lasting about 1.5 hr. Participants were instructed that they should take part in both sessions, which were to be separated by a week's time.

At the beginning of the session for hefting and judgment, the experimenter introduced and demonstrated the hefting motion to participants. The object was set on the participant's palm by the experimenter. The participant's eyes were closed whenever the experimenter was handling the objects but open otherwise. The object and hand were then to be bounced up and down at the wrist by an oscillation of the forearm about the elbow. The experimenter took a set of anthropometric measures of each participant including age, sex, height, weight, hand span, hand length, palm width, and arm length. Experimenter and participant then stood on opposite sides of a 1-m high table to perform the hefting and judgment task. Each of the six different size series was presented on the table, one size series at a time, with the sizes presented in a random order. The balls in each size were arrayed from left to right before the participant in order of increasing weight. Next, the participant was asked to heft each of the objects in order of increasing weight and to pick in order of preference the top three preferred objects for throwing to a maximum distance, that is, a first, second, and third choice. After all weights were hefted, the participants were allowed to select, by pointing, objects that they would like to heft again to help make their choice. Three preferences, as opposed to one, were used so that we could use a weighted average as an estimate of preferred size and to provide a better estimate given the necessarily discrete way the objects sampled the weight continuum. The same hefting and judgment procedure was repeated for each of the six different object sizes. To record the judgments (and later the throwing), a random code was used to label the objects so participants could not use the labels to identify particular weights. Small labels were kept out of view on the bottom of the objects on the table and in the hand.

The throwing session took place on a large outdoor grass-covered field. The weather conditions were calm. The experiment was performed during the fall. Upon arrival, each participant was allowed to warm up his or her throwing arm by doing some stretches and throwing of a tennis ball. The balls were distributed randomly on the ground behind where the participant was to stand

Table 1
Object Weights Within Size

Diameter (m)	Object weight (kg)							
	1	2	3	4	5	6	7	8
.025	.004	.006	.009	.013	.021	.032	.050	.077
.050	.007	.011	.016	.025	.039	.061	.094	.146
.076	.017	.027	.042	.064	.100	.155	.240	.372
.102	.040	.062	.096	.149	.231	.358	.555	.860
.127	.048	.075	.116	.180	.278	.432	.668	1.036
.152	.100	.155	.240	.372	.576	.892	1.384	

while throwing the balls. The participant was handed the balls in a random order and asked to throw each to a maximum distance. The participant was allowed to use his or her preferred throwing style as long as the throw was overarm and only a single step was taken before the throw. Each participant threw the entire set of objects three times yielding a total of 141 throws (47 balls × 3 trials). There were two experimenters: One was to hand the participant the objects to be thrown and record the data; the other was responsible for marking the landing position of the thrown objects, measuring distances, and recovering the thrown objects. After each throw, the distance was measured by one experimenter and read to the other experimenter who was recording. Throwing distance was measured from the origin where the thrower's foremost foot landed before the throw to the position at which the thrown object first contacted the ground.

Results and Discussion

As shown in Figure 1, the results from Experiment 1 replicated the results of G. P. Bingham et al. (1989). For objects of a given size, participants were able to pick the optimal weight for maximum distance throws. The selected objects were actually thrown to the farthest distances.

In the hefting and judgment session, participants tended to show strong preferences for the objects that they judged to be optimal. As in the original study, the mean of the chosen weights for each size was computed by weighting judgments according to preference: first chosen weight was multiplied by .5, second chosen weight was multiplied by .33, and third chosen weight was multiplied by .16.

As can be seen from Figure 1, the mean of the chosen weights increased across increases in the size of the objects. A repeated-measures analysis of variance (ANOVA) on chosen weights was performed, with size as a repeated-measure factor. Size was significant, $F(5, 35) = 26.6$, $p < .001$. Weight increased with size. Also the difference between mean chosen weights was much smaller for the two largest and two smallest sizes than for the intermediate sizes. A test of within-subject contrasts indicated that
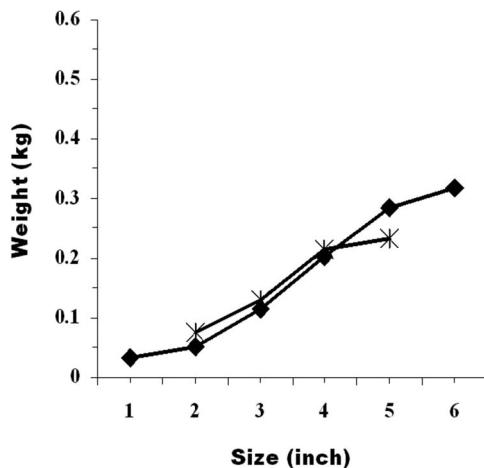
the means of the chosen weights were significantly different from one another proceeding from the .050-m ball to the .127-m ball ($p < .01$), whereas the differences between the two smallest (.025-m and .050-m) and two largest (.127-m and .152-m) balls were not significant. These findings were similar to those in the previous study showing that increases in preferred weights are bounded for the largest objects. As described in G. P. Bingham et al. (1989), this bound indicates that a transition between throwing action modes may occur when the size of objects changes from intermediate to large. The current study also showed the existence of a boundary for the smallest objects. This might be because the mean weights chosen for the smallest objects correspond to the maximum weight that can be thrown without a decrement in release velocities (Cross, 2004). See the General Discussion for more on this point.

Next, we turned to analysis of throwing performance. To compute mean throw distances across participants for preferred and nonpreferred weights in each size, it was necessary to align the data for each object size in terms of the mean preferred weights for each participant. Although participants exhibited the same pattern of weight choices across different sizes (namely, larger weights for larger sizes), the particular weights varied among participants partly as a function of the size of the participant. Throwers also varied in throwing abilities as indicated by the mean throwing distances. However, again, the same pattern of distances was exhibited by all participants, namely, the chosen object weights (first choice, second choice, and third choice) were thrown to the farthest distance. For each object size and participant, object weights were divided by the participant's mean preferred weight in the size. This displaced normed weight levels relative to one another across participants for purposes of computing mean distances for given weight levels. Because weight levels were distributed according to the geometric series, we log transformed the normed weight levels to achieve approximately equal intervals between levels. Next, we put the data into bins whose size was selected to yield one data point for each participant in each bin. We then computed mean distances for each bin. Because weights were normalized by the preferred weights and then log transformed, 0 on the log (normed weight) axis corresponded to the weight selected by hefting. The mean throw distances formed a surface in a Z (distance) × X (size) × Y (log normed weight) space.

As shown in Figure 2, the surface varied in two respects. First, distances exhibited an inverted-U pattern for each object size. Second, distances decreased with increasing size because of the increased air resistance in projectile motion. The peaks of the inverted-U curves were aligned to form a ridge line representing the mean maximum distance throws across object sizes. We projected this ridge line onto the size by log (normed weight) plane, that is, the floor in the figure. If the ridge line projected directly onto the 0 axis of the log (normed weight), then participants would have been perfectly accurate, on average, at selecting maximum throwable objects. The projected ridge line oscillated in close proximity to this axis indicating that participants were accurate in selecting optimal objects for throwing. This correspondence of the chosen weights to the weights being thrown farthest suggested that the task of hefting by hand provided throwers good access to the throwability of the object for maximum distance throws. We confirmed this in the following analysis.
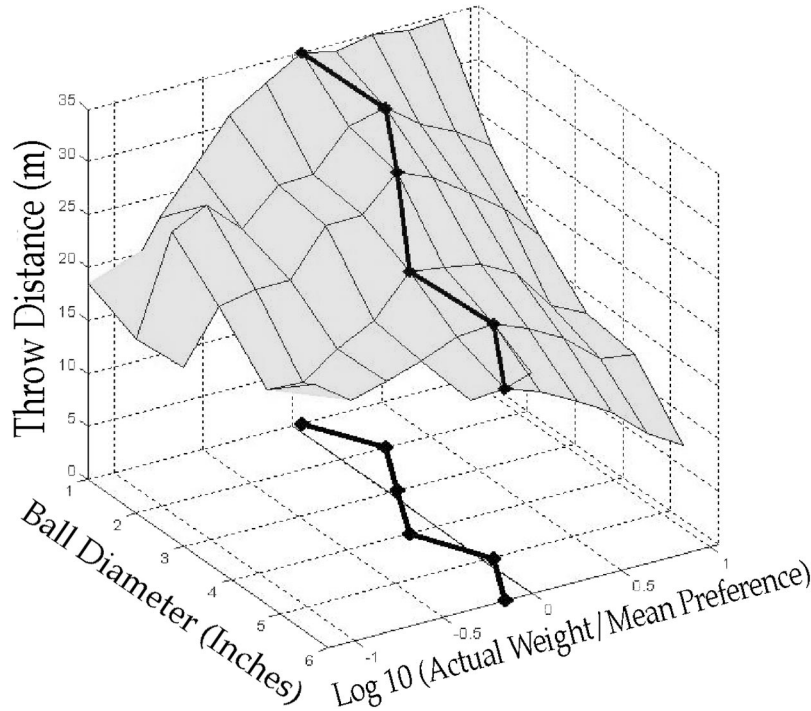

Figure 1. Mean of weights selected by participants as a function of size in Experiment 1 (filled diamonds) and the original G. P. Bingham et al. (1989) study (stars).

Figure 2. A surface representing mean thrown distances in Experiment 1 as a function of two variables, size and weight. The line following the peak ridge of the surface projects onto the size–weight plane describing the size–weight scaling relation for preferred objects. When the projected line aligns with the 0 value on weight axis, the preferred weight was thrown to the farthest distance.

To analyze distances as a function of the participants' choices, we performed a series of analyses. First, for each participant and each object size, we computed a mean throw distance for all the nonchosen weights and then for the first-, second-, and third-choice weights, respectively. We performed a repeated-measures ANOVA on these mean distances, with size (1–6) and choice (first, secnd, third, not chosen) as factors. Both size, $F(5, 35) = 50.1$, $p < .001$, and choice, $F(3, 21) = 23.5$, $p < .001$, were significant, but the interaction was not ($p = .4$). In all sizes, chosen weights were thrown farther than nonchosen weights, and smaller sizes were thrown farther than larger ones. In all sizes but one (the smallest), first- and/or second-choice weights were thrown farther than the third-choice weights.

Next, to reveal and test more of the surface shown in Figure 2, we extrapolated choices beyond the top three choices: The top three choices were always of contiguous weights in the weight series for a given size. We assigned the mean throw distances of the next lightest and next heaviest objects to those chosen as a fourth choice, the mean of the distances for the next lightest and next heaviest to the fifth choice, and so on (traveling down the arms of the inverted-U curves) for a total of six choices in order. Thus, we obtained distance data as a function of choices and sizes. A polynomial regression analysis was performed on mean distances in each size to yield the best fit polynomial regression curves shown in Figure 3. (The fit was also made to the combined participant data reported in parentheses in the following paragraph.)

The polynomial regression was significant in all cases: for the .025-m ball, $r^2 = .98$, $p < .01$ ($r^2 = .50$, $p < .001$); for the .050-m

ball, $r^2 = .89$, $p < .05$ ($r^2 = .19$, $p < .01$); for the .076-m ball, $r^2 = .98$, $p < .01$ ($r^2 = .48$, $p < .001$); for .102-m ball, $r^2 = .98$, $p < .01$ ($r^2 = .69$, $p < .001$); for .127-m ball, $r^2 = .98$, $p < .01$ ($r^2 = .47$, $p < .001$); and for .152-m ball, $r^2 = .95$, $p < .05$ ($r^2 = .47$, $p < .001$). The representation of the distance curves by quadratics
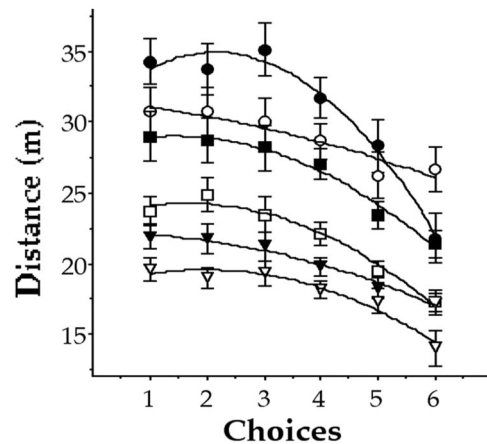

Figure 3. Mean thrown distance as a function of size and choice. Choice from 1 to 6: 1 represents the most preferred object, 6 represents the least preferred object. See text for explanation. Sizes: 1-in. ball (filled circles), 2-in. ball (open circles), 3-in. ball (filled squares), 4-in. ball (open squares), 5-in. ball (filled triangles), and 6-in. ball (open triangles; i.e., from 2.5 cm to 15 cm in diameter). The curves represent best fit quadratic regression. Error bars represent standard errors.

reflects the fact that each curve contained a peak corresponding to the maximum distance. We used the resulting quadratic function to compute the peak point in the curve by taking the derivative of the quadratic function to get a value on the x-axis where the increase of Y (that is distance) achieved zero, thus yielding the peak point on the curve. The resulting values (rounded to integers) are 2 for the .025-m ball, 1 for the .050-m ball, 1 for the .076-m ball, 1 for the .102-m ball, 1 for the .127-m ball, and 2 for the .152-m ball. Both the first choice (for the .025-m, .076-m, .102-m, and .127-m balls) and the second choice (for the .050-m and .152-m balls) yielded the maximum throwing distance, which again confirmed our hypothesis that participants are able to pick the optimal objects for maximum distance of throws.

Experiment 2: Using the Elbow or Foot to Heft Objects for Overhand Throwing

In the first experiment, the results of G. P. Bingham et al. (1989) were replicated. Participants were able to perceive by hefting which combinations of object size and weight were optimal for throwing to a maximum distance using an overarm throw. The judgments were performed using the arm and hand to heft the objects. G. P. Bingham et al. argued that this perception was accomplished via a type of smart perceptual mechanism. This particular smart mechanism hypothesis assumes that the dynamics of the arm and hand as used in hefting are related to the dynamics of the arm and hand as used in overarm throwing, and this relation allows hefting to yield information about objects with respect to throwing. In this case, the smartness lies specifically in this relation. This hypothesis entails the need to heft the objects using the same limb that is able to execute the skilled overarm throwing and exhibit the dynamics of the act.

A notable aspect of the results from the hefting task is that the preferred weights follow the size–weight illusion function. According to that function, to be perceived of equal weight, different sized objects must weigh different amounts, namely, bigger objects must weight more. The illusion phenomena are quite robust, and studies have shown that the phenomena persist when object size is perceived visually, whereas object weights are perceived by testing objects suspended on wires and pulleys and other means that completely alter the dynamics of hefting using the hand (e.g., Ellis & Lederman, 1993; Masin & Crestoni, 1988). We then tested the smart mechanism hypothesis about hefting for throwing by asking participants to perform the hefting by using another limb configuration, that is, by hefting the objects on the bent elbow (using the upper arm) or on the foot (using the leg). In each case, this would enable participants to see the size of the object and feel its weight. So, the relevant dimensions could be perceptually accessed but not by hefting in the hand. Two different groups of participants were tested. One group was asked to heft the objects using their upper arms and shoulders with the objects resting on their (folded) elbow. A second group was asked to heft the objects using their legs with the objects resting on the instep of their foot. In each case, participants were asked to pick preferred objects for overarm throwing to a maximum distance. The expectation from the smart mechanism hypothesis was that participants should not be able to judge optimal objects for overarm throwing when hefting with these other limbs. Participants in Experiment 2 were only tested in a single session in which they performed the hefting

judgments. The judgment results were compared with the results of the previous experiments in which participants did the hefting using their hand.

Method

Apparatus. Objects made for Experiment 1 were used again in Experiment 2 for hefting and judgment. An adjustable armband with Velcro closure was worn by participants either on their elbow or their foot, respectively. A small piece of Velcro was attached to each object so that the object could be Velcroed to the limb to enhance its stability in resting on the limb while being hefted.

Participants. Sixteen Indiana University undergraduates from the Department of Psychology were paid at a rate of $8 per hour for participation. Two groups of 8 participants were tested. Half of the participants in each group were men, and half were women. Participants were required to be capable of throwing objects and to have had some prior experience and skill at overarm throwing, to have good (corrected) vision, and to be free of motor impairments.

Experimental procedure. The procedure was the same as in Experiment 1, but this time, either the elbow or the foot was used to perform the hefting and judgment task. Participants were randomly assigned to one of two groups. In one group, participants used their elbow to heft and make the judgments. They were asked to wear the armband by wrapping it comfortably around the elbow of their dominant arm and then bend the arm to form an angle at the elbow so that the object could sit on the supporting area formed by the arm in this posture, stabilized by the contact between the Velcro on the object and on the armband. The other group used their foot to heft and make the judgments. They were asked to wear the armband by wrapping it comfortably around the foot of their dominant leg and then lift the foot to form an angle at the ankle so that the object could sit on the supporting area formed by this posture, again stabilized by the contact between the Velcro on the surface of the object and the armband. Once the object was sitting steadily on the elbow or foot, hefting was performed by oscillating the limb and object up and down. (Participants using the foot were seated during the task with one leg crossed over the other.) All judgments were based on the use of the arm and hand to perform an overarm throw.

Results and Discussion

Our hypothesis was that participants would not be able to judge the optimal weight for maximum distance throws by hefting with nonarm–nonhand limbs. This was verified by Experiment 2. Results showed that participants picked heavier weights when they hefted objects by elbow or foot than they did by hand (see Figure 4).

A mixed design ANOVA was performed on chosen weights, with size as a within-subject factor and hefting limb (elbow or foot) as a between-subjects factor. The only main effect was size, $F(5, 70) = 40.8$, $p < .001$. The difference between hefting limbs was not significant, and there was no interaction between the size and limbs. When comparing foot with hand hefting in Experiment 1, the size effect remained, $F(5, 70) = 43.5$, $p < .001$, and the difference between limbs became significant, $F(1, 14) = 4.9$, $p < .05$, as well as the interaction between the limbs and size, $F(5, 70) = 2.5$, $p < .04$.

Furthermore, as shown in Figure 5, judgment by foot or elbow was more variable than judgment by hand (although the judgment

by elbow hefting was only marginally so). These findings suggest that hefting by a nonhand limb (foot or elbow) for maximum distance overhand throw resulted in an elevated judgment of weight. Nevertheless, the effect of size remained, namely, the mean of the chosen weights increased as size increased.

Experiment 3: Hefting Using the Foot to Judge Objects for Throwing Using the Foot

We found in Experiment 1 that the hefting in the hand provided good access to the throwability of objects for maximum distance overhand throws. However, in Experiment 2, we found that hefting using a foot or elbow did not yield comparable judgments. The objects selected for throwing were systematically heavier than those selected when objects were held and hefted in the hand. The participants did not select objects optimal for overhand throwing. The smart mechanism hypothesis predicts that the dynamics of hefting with the hand provides perceptual access to the dynamics of throwing with the hand. Hefting with another limb would not provide such access because differences in the structure of the limb would entail differences in the dynamics. So, this result was consistent with the particular smart mechanism hypothesis. However, it is possible that the results of Experiment 2 are consistent with this smart mechanism hypothesis in two ways. Namely, it is possible that hefting with the foot provides information about optimality for throwing with the foot. The leg is a more massful and stronger limb and may require heavier objects for optimal throwing. We tested this possibility in Experiment 3.

As in Experiment 1, participants were tested in two sessions: one for hefting and judgment and another for throwing. However, this time, both the hefting and the throwing were performed using the foot and leg. We expected the hefting data to replicate the foot hefting data from Experiment 2. We also expected that participants might be successful in judging which objects they could throw the farthest distance using their foot to throw them. Participants could not be expected to have had much experience in using their foot to throw, so we expected both the judgment and throwing results to
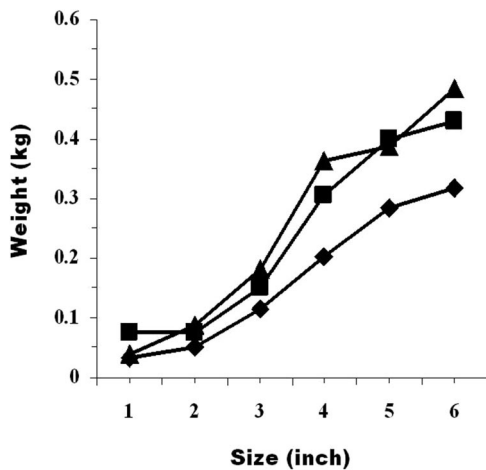

Figure 5. Standard deviation of the chosen weight as a function of size in Experiments 1 and 2. Hefting using the hand is represented by filled diamonds. Hefting using a foot is represented by filled triangles. Hefting using an elbow is represented by filled squares.
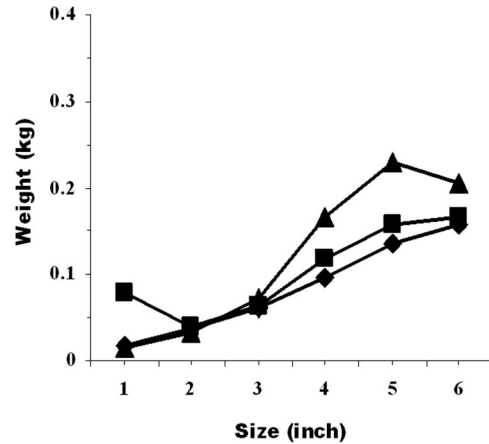
be variable or noisy compared with the previous results obtained when participants used their hands.

Method

Apparatus. The same objects from Experiment 1 were used both for hefting and throwing. For hefting, the armband with Velcro closure was used again. To provide improved stability of the object on the foot, especially for throwing, a special cup was developed to hold the objects for both hefting and throwing. We used an extra resin sphere of the largest size and cut it in half with a section also cut to form a scoop, threaded the armband (or footband) through slits cut in the bottom, then fastened it on the ankle with the open side of the scoop oriented to the front so that it would not impede the forward motion of the object leaving the scoop. The scoop not only provided a steady support for an object sitting on the foot, but it also facilitated the throwing. To further facilitate the throwing, a length of fishing line was tied to an eye that was attached to each object so that the participant could support the object by holding the end of the line in the hand to suspend the object in the scoop, and then as the leg was swung, the line was released as the object was launched from the foot.

Participants. Eight Indiana University undergraduates from the Department of Psychology were paid at a rate of $8 per hour for participation of the two sessions of the experiment. Half of the participants were men, and half were women. They were not required to have had prior experience throwing a ball with their foot. Participants were required to be capable of throwing objects with their hand and to have had some prior experience and skill at overarm throwing, to have good (corrected) vision, and to be free of motor impairments.

Experimental procedure. The same procedures as in Experiment 1 were used with the exception that hefting and throwing were performed using the scoop on the dominant foot and participants judged optimal throwability using the foot to throw. Note that participants did not kick these balls but threw them by resting them on their feet and then pulling their feet and object back and then swinging them rapidly forward to launch the ball.

Figure 4. Mean of weights selected by participants as a function of size in Experiments 1 and 2. Hefting using the hand is represented by filled diamonds. Hefting using a foot is represented by filled triangles. Hefting using an elbow is represented by filled squares.

Results and Discussion

In the hefting session, the size–weight effect was preserved. The mean chosen weights increased with size. An ANOVA was performed on chosen weight, with size as a within-subject factor. Size was significant, $F(5, 35) = 13.2$, $p < .001$. However, in contrast to pervious results, no boundary was found for weights. The chosen weights increased at every size increment. The test of within-subject contrasts yielded a significant difference in weight for every increase of size ($p < .05$). In addition, the results replicated the foot hefting data from Experiment 2 by exhibiting an elevated judgment of the optimal weight compared with Experiment 1 (see Figure 6).

An ANOVA was performed on chosen weights, with size as a within-subject factor and experiment as a between-subjects factor. Comparing foot data from Experiments 2 and 3, the main effect for size was significant, $F(5, 70) = 32.3$, $p < .001$, whereas there was no significant difference between the foot judgments in two experiments. When we compared the foot hefting data in Experiment 3 with the hand hefting data in Experiment 1, we found no significant difference for hefting limbs but a significant size effect, $F(5, 70) = 27.3$, $p < .001$, as well as a nonsignificant interaction between hefting limbs and size, $F(5, 70) = 2.3$, $p < .06$. The reason the latter comparison failed to reach significance is that the variability for judgment by foot was very high in Experiment 3. The standard deviations of the chosen weight for foot hefting in both Experiment 2 and 3 were both higher than for hand hefting, hence, the judgment by the nonhand limb hefting was much noisier and variable than hefting by hand (see Figure 7).

In Experiment 1, the first, second, and third choices of preferred objects were always of contiguous weight levels in the weight series for each size. We noted that this was not true of judgments in Experiments 2 and 3. In fact, the judgments looked rather random. This would be consistent with the very high level of variability. To verify this possibility, we simulated a judgment by randomly picking a weight from the available weight list (eight
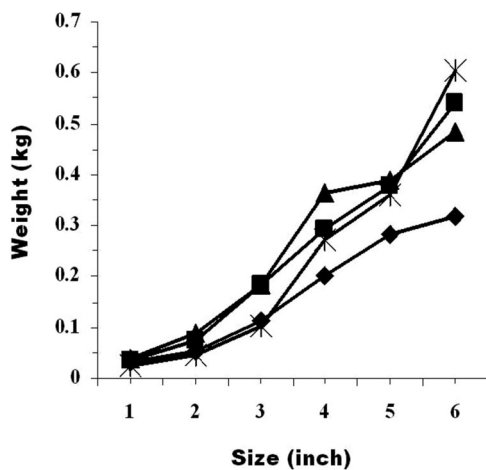

Figure 7. Standard deviation of chosen weights as a function of size in Experiments 1, 2, and 3. Hefting using a hand is represented by filled diamonds. Hefting using a foot in Experiment 2 is represented by filled triangles. Hefting using a foot in Experiment 3 is represented by filled squares. The mean of weights chosen randomly is represented by stars.
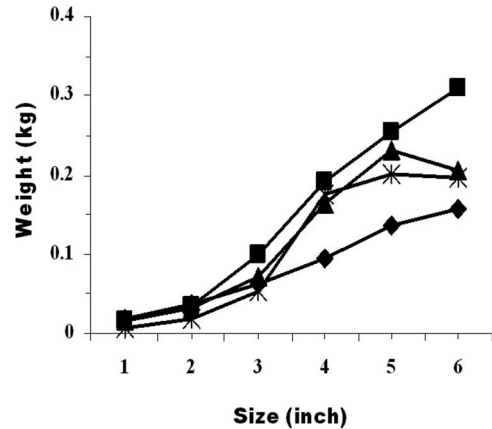
weights) within each size. We picked three tickets of paper (on which weights were listed) from a hat without replacement and then replaced the three tickets and repeated the pick eight times to reproduce the data for 8 participants. The means and standard deviations of the random selection are shown in Figures 6 and 7. An ANOVA was performed on these chosen weights, with size as a within-subject variable and the selection method as a between-subjects variable. Although size was significant as before ($F[5, 70] = 31.5$, $p < .001$, for foot hefting; $F[5, 70] = 33.7$, $p < .001$, for random selection), no significant difference was found between foot hefting and random selection. However, the hand hefting was found to be significantly different from the random selection, $F(1, 14) = 5.4$, $p < .04$, and in that case, the interaction between size and selection method was also significant, $F(5, 70) = 4.7$, $p < .001$. These results suggested that both foot hefting judgments were random selections; neither of them were accurate in determining the optimal weights for maximum distance throws. Once again, when we looked at the variance for different selection methods (see Figure 7), we found both foot hefting judgments possessed comparable standard deviations with the random selection data, both higher than the hand hefting judgment, which remained the most consistent.

Next, we related participants' judgments to their throwing performance. Given the discovery that the judgments were fairly random, we expected two results with respect to the throwing. First, throwing performance should be quite poor, reflecting a lack of skill in throwing using the leg and foot. We expected this because skill in perceiving the affordance and skill in using the affordance should be comparable. Second, we expected mean judgments to be inaccurate in respect to actual throwing performance. It would be worrisome if they were not.

For each participant and size, we averaged the throwing distances for all not-chosen weights to compare with those of the first, second, and third chosen weights (see Figure 8).

An ANOVA was performed on throwing distance, with size and choice as two within-subject factors. Only size was found to be significant, $F(5, 35) = 9.2$, $p < .001$. Neither choice nor its

Figure 6. Mean of weights selected by participants as a function of size in Experiments 1, 2, and 3. Hefting using a hand is represented by filled diamonds. Hefting using a foot in Experiment 2 is represented by filled triangles. Hefting using a foot in Experiment 3 is represented by filled squares. The mean of weights chosen randomly is represented by stars.
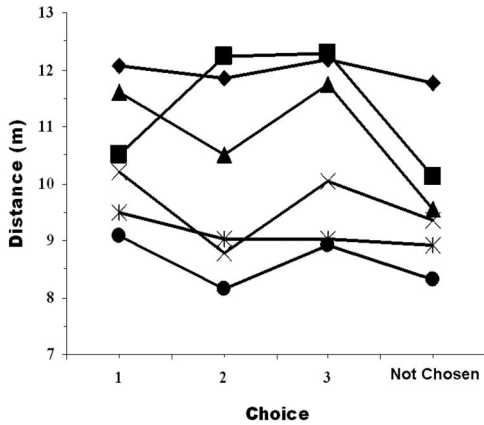
Figure 8. The mean thrown distance in Experiment 3 as a function of size and choice. Sizes: 1-in. ball (filled diamonds), 2-in. ball (filled squares), 3-in. ball (filled triangles), 4-in. ball (crosses), 5-in. ball (stars), and 6-in. ball (filled circles; i.e., from 2.5 cm to 15 cm in diameter).

interaction with size was significant. The distance curves were flat across the choices. This finding demonstrates that hefting using a foot did not provide enough information about the objects to enable participants to select optimal objects for throwing with the foot. However, size still played an important role in determining the throwing distance, namely, larger objects were thrown to a shorter distance than smaller objects.

Finally, the surface plot was developed again to provide an overview of the interrelationship among the size, weight, and throwing distance (see Figure 9). The current surface plot had the following properties: First, the surface again tilted down toward the floor as the size of object increased, which means size still played an important role in determining the throwing distance. This was presumably because size plays a strong role in projectile dynamics as we show in Experiment 4. Second, the maximum throwing distances of foot throwing were in general substantially shorter than hand throwing (15 m vs. 35 m), which indicated foot throwing was a much more difficult and/or less skilled task compared with the overarm throwing. This confirmed one of our expectations. Third, the ridge line of the surface, when projected on the floor of the graph, deviated from the reference line where the actual weights were equal to the preferred weights. The pro-
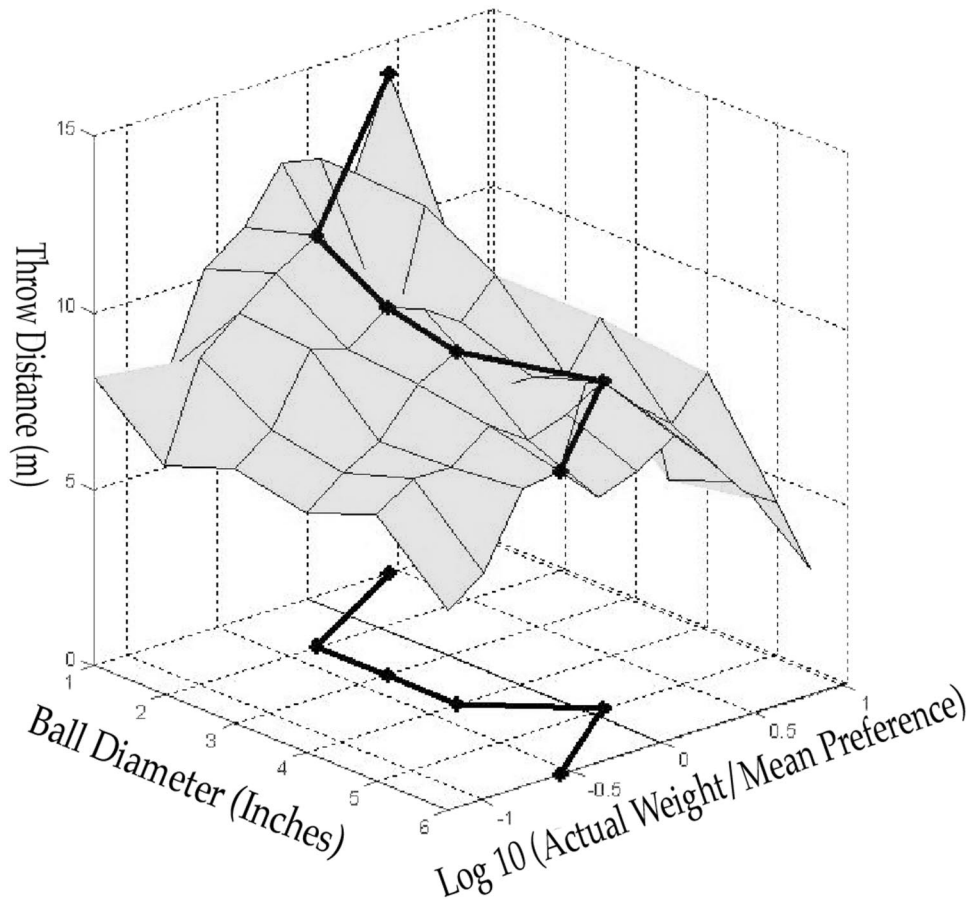

Figure 9. A surface representing mean thrown distances in Experiment 3 as a function of two variables, size and weight. The line following the peak ridge of surface projects onto the size–weight plane describing the size–weight scaling relation for preferred objects. When the projected line aligns with the 0 value on weight axis, the preferred weights was thrown to the farthest distance.

jected line mostly lay on the left of the reference line (four points lay between 0 and −0.5 on the axis), which means the actual weights being thrown the farthest were in general lighter than expected. The foot hefting judgment tended to overestimate the optimal weight for maximum distance of foot throws. This confirmed our other expectation that judgments would be inaccurate.

Experiment 4: Determining the Role of Object Size in the Dynamics of Throwing Versus Projectile Motion

The particular smart perceptual mechanism hypothesis of G. P. Bingham et al. (1989) is that object size and weight affect the dynamics of hefting in a way similar to the way they affect the dynamics of throwing so that hefting can provide information about the effect of object size and weight on throwing. Thus, the hypothesis requires that both object size and weight affect the dynamics of overarm throwing. In Experiment 4, we tested this assumption.

It is obvious in the throwing results of Experiment 1 that object size affects throwing distances. Distances decreased as object size increased, presumably because of the increased air resistance of larger objects. However, size played another role. The greatest distances were reached by objects of a particular optimal weight in each size, and the optimal weight varied as a function of size. The assumption required for our smart mechanism hypothesis is that this functional relation between size and weight reflected a joint effect of size and weight on the dynamics of throwing. However, it is possible that object size only affected the dynamics of projectile motion with no effect on the dynamics of throwing. It is this possibility that we then sought to test. It is known that object weight affects throwing (e.g., Cross, 2004). Release velocities are known to decrease as the weight of thrown objects increases. However, the effect of object size on throwing is unknown.

We proceeded as follows. First, we tested 4 skilled throwers to measure the release angles as they performed maximum distance throws of our test objects. Next, we used the mean measured release angles together with the mean thrown distances from Experiment 1 and object sizes and weights in a simulation of the dynamics of projectile motion to derive the release velocities. We compared the resulting release velocities with results in the literature of studies on throwing measuring the effects of object weights on release velocities. We found good correspondence in these results. Accordingly, we next used a model of the effect of weight on release velocities in throwing together with our mean measured release angles, object sizes, and weights in simulations of projectile motion to compute distances of throws. This model entailed no effect of object size on throwing, only on projectile motion. The question was how well might this model replicate our mean throw distances.

Method

Apparatus. Twenty-four of the objects from Experiment 1 were used for throwing. All eight weights were used in three of the sizes: 1 in. (2.5 cm), 3 in. (7.5 cm), and 5 in. (12.5 cm). In addition, a digital video camera (SONY Handycam DCR-DVD605) on a tripod was used to record the throwing. The sampling rate was 30 fps. The digital images were subsequently input to a computer and processed using Protractor 4.0 software (Iconico, 2007) that measured the release angles.

Participants. Four adults at Indiana University volunteered to participate in the experiment. All were skilled at overarm throwing. Two were Olympic level athletes in badminton (one man and one woman). One was very skilled in playing cricket. All participants were in their late 20s. The last was a 52-year-old man skilled in baseball. Participants all had good (corrected) vision and were free of motor impairments.

Experimental procedure. Participants were tested in a large field house–gymnasium at Indiana University. Participants stood about 5 m in front of a cinderblock wall that provided a visible grid and thus gravitational frame of reference. The digital camera was positioned on its tripod at shoulder height and directly to the side of the thrower (i.e., at 90° to the direction of throws) at a distance of about 8 m. The participants warmed up their arms by throwing balls back and forth to one another and also by performing some maximum distance throws. Then each participant performed maximum distance throws of all 24 objects, thrown in a random order. Subsequently, the digital video recordings were downloaded to a computer for analysis. For each throw, two frames were used to measure angle of release, the first frame in which the ball had left the hand, and the following frame. The angle of the path of the ball relative to the horizontal in the gravitational frame was measured using a digital protractor.

Results and Discussion

Release angles did not vary systematically with either object size or object weight. All participants exhibited mean release angles that were significantly less than the optimal release angle of 36°. The overall mean release angle was 24°. We performed a multiple regression on release angles, with object size and log weight vectors as continuous independent variables and a vector consisting of their product, to assess the interaction. The result did not reach significance ($p > .10$). None of the vectors accounted for a significant portion of the variance. The distribution of mean release angles (with standard error bars) for the 24 objects is shown in Figure 10 together with a best fit line representing a simple regression of log(weight) on the mean release angles. The variation was random, and thus release angles of throws were best represented by the overall mean release angle of about 24°.

Next, we used the mean release angle together with the mean throw distances found in Experiment 1 and the object sizes and weights to perform simulations of projectile motion to discover the corresponding release velocities. For a projectile with air resistance and quadratic drag, the following parameters are considered in predicting the distance of travel: the projectile's mass and the cross-sectional area, release angle, release velocity, the air density, and the drag coefficient. With the available weights, sizes, release angle, and thrown distances, we only needed the drag coefficient and air density to recover the release velocities. According to Parker (1977), the appropriate drag coefficient for our spheres and velocities of travel is 0.5 and air density is 1.22 kg/m^3. Using these values, we employed standard numerical methods to integrate the nonlinear equations of motion (see, e.g., Parker, 1977) to discover the corresponding release velocities for each throw by varying the initial velocities to find those required to generate the throw distances.

We found that the recovered release velocities followed a function of object weight: As object weight increased, the release
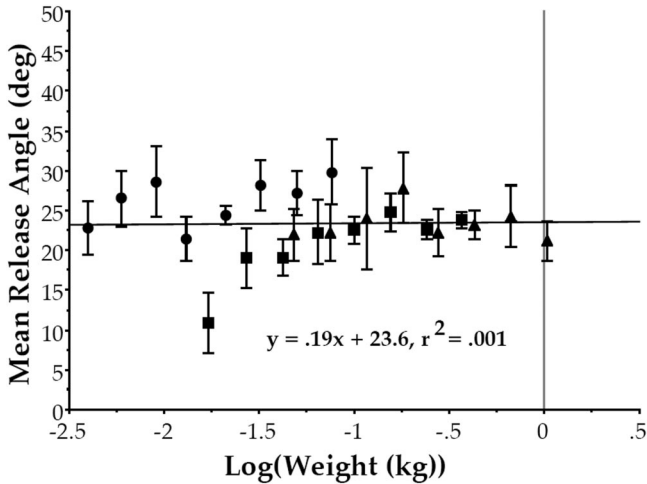
Figure 10. Mean release angles in Experiment 4 plotted as a function of the log weight of the objects thrown. Filled circles: 1-in. (2.5-cm) balls. Filled squares: 3-in. (7.6-cm) balls. Filled triangles: 5-in. (12.7-cm) balls. Error bars represent standard errors.

velocity decreased. However, velocities did not begin to decrease until the object weight reached .05 kg (log weight = −1.30; see Figure 11). A separate linear regression analysis was performed on the data lying on each side of a weight value of .05 kg. For weights less than .05 kg, the linear regression of weight on velocity was not significant (r^2 = .12), $F(1, 16)$ = 2.0, p > .15, and the mean velocity was 23 m/s. However, for weights greater than .05 kg, the linear regression was significant (r^2 = .85), $F(1, 29)$ = 147.8, p < .001, with a negative slope. We transformed the regression function to a power law: Velocity = 14.8 × (Weight)$^{-0.15}$. These findings replicate those of Cross (2004), who investigated the

effect of object weight on release velocities. He measured release velocities directly and modeled the resulting relation between velocity and weight with the same power law. For object weights greater than .05 kg, the release velocity followed a power function of weight with an exponent of −0.15. Below .05 kg, the projectile weight did not affect release velocities, which were constant at a maximum release velocity of about 20 m/s.

This functional dependence of release velocity on weight, but not on size, implied that only weight affects the dynamics of throwing and that size does not. Instead, size must play a role in producing the pattern of throw distances that we observed by affecting the dynamics of projectile motion. That is, throw distances would be a function of the effect of object weights on throwing together with the effects of object weight and size on projectile motion. If this is the case, then we should be able to simulate the pattern of mean distances of throws using the variations in release velocity caused only by weight (not size) variations. We ran the simulations of thrown distances again using the weight-release velocity function. Two sets of release velocities were employed. For objects equal to and lighter than .05 kg, we used a constant velocity of 23 m/s. For objects heavier than .05 kg, we used a set of velocities generated by the power law (V = $14.8 W^{-.15}$). Otherwise, we used the same values previously used for release angle, drag coefficient, air density, and sizes and weights of the objects. The result reproduced our distance data remarkably well, accounting for 82% of the variance (r^2 = .82), $F(1, 46)$ = 208.1, p < .001 (see Figure 12). The resulting regression function was as follows: Mean throw distance = (.96 × simulated distance) + 1.42. Additionally, the simulated distances exhibited the same effects of size and weight as exhibited by the data: Distances decreased with increasing size (because of the increased air resistance in projectile motion), there was an optimal weight level for each size at which objects were thrown to the farthest distance, and those optimal weights increased with in-
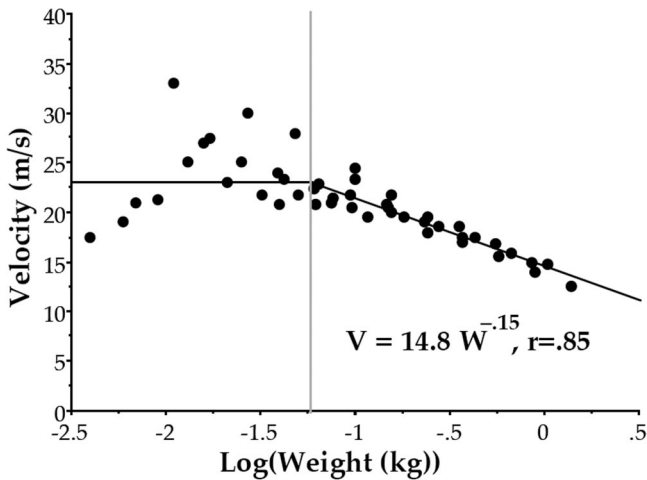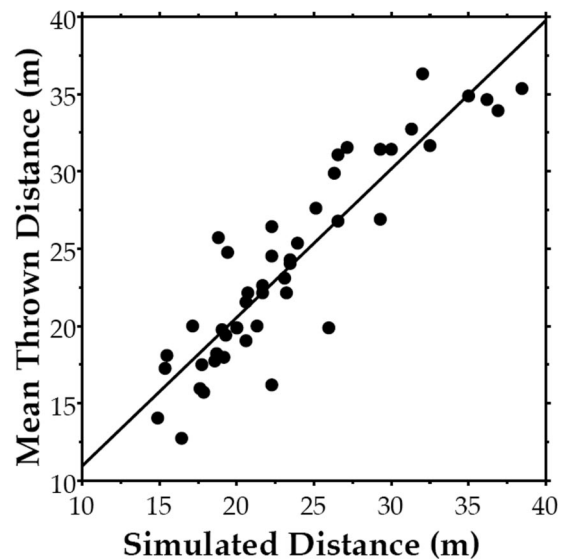

Figure 11. The recovered release velocities as a function of log object weights. The vertical line at log weight = −1.30 marks the point at which weight begins to effect release velocity. The linear regression on the left side of the reference line shows no correlation between release velocity and object weight (R^2 = .08), whereas the linear regression on the right side of the reference line shows strong negative correlation between release velocity and object weight (R^2 = .85).

Figure 12. A scatterplot of the simulated thrown distances versus the thrown distances in Experiment 1 together with a line fit by least square regression.

creasing object size exactly in the simulation as in the data from Experiment 1 (see Figure 13). Thus, according to these results, the affordance property is emergent from the combined dynamics of throwing and projectile motion.

General Discussion

We investigated the ability of people to judge the optimal weight of different sized objects for maximum distance throws. Experiment 1 was performed to replicate G. P. Bingham et al. (1989). The results confirmed the earlier finding that the affordance property, optimal object to be thrown to the farthest distance, can be well perceived by hefting an object in the hand. The weights chosen by hefting were thrown to the farthest distance. As found previously, the preferred weights increased with increasing object size. Next, we tested an assumption required for the hypothesis that this hefting functions as a certain kind of smart mechanism. The assumption is that a dynamically similar limb (i.e., an arm and hand) would have to be used for both hefting and throwing. In Experiment 2, we tested whether people can still judge the optimal weight for overarm throwing when hefting using a limb different from the arm and hand. The results showed that people picked heavier weights when they hefted objects using either the elbow or the foot, and the judgments were more variable than those generated using the hand. In Experiment 3, we investigated the relationship between hefting using the foot and throwing using the foot. Again, a variable and elevated judgment of optimal weight was found, and the thrown distances were very small compared with when participants used the hand. This indicated that throwing using a leg and foot was simply unskilled. Furthermore, lighter weights than those chosen were thrown to the farthest distance, so the judgments were inaccurate. Finally, the selected weights were not different in respect to mean or variability from a random selection. The findings from Experiment 2 and Experiment 3 indicated that hefting using the specific skilled limb is necessary for accurate selection of the optimal objects.

The results of these experiments supported the smart mechanism hypothesis of G. P. Bingham et al. (1989), which presumes that object size and weight affect hefting in a way similar to their effect on throwing, so that hefting can serve us a window on the effect of object size and weight on throwing. The objects selected as optimal were of increasing weight for increasing sizes. G. P. Bingham et al. had found evidence that grasping larger objects causes the stiffness of the wrist joint to increase. They suggested that heavier objects are selected accordingly to preserve the frequency and/or amplitude of motion about the wrist so as to preserve relative timing of motions in throwing. If so, then both hefting and throwing would be affected by variations in object size in the same way, and thus hefting would provide perceptual access to requisite variations in weight given changes in size.

However, the distance of throws is determined ultimately by both the dynamics of throwing and the dynamics of projectile motion. The interface between the two is the release angle and velocity. We found in Experiment 4 that skilled throwers failed to exhibit optimal release angles. Release angles varied about a mean angle equal to 24°, less than the optimal angle of 36°. The variations were random. So, release angle is best represented by the 24° mean. If both size and weight of thrown objects affect the dynamics of throwing, then the effect should be apparent in variations of release velocities. Previous studies of throwing have shown that object weight does affect release velocity (e.g., Cross, 2004), but there have been no studies of the effect of object size on release velocity. We used our data to investigate this question through simulations of projectile motion.

First, we worked backwards from given distances of throws for each object size and weight (taken from the means in Experiment 1) using a simulation of the dynamics of projectile motion together with the mean measured release angle to derive release velocities. We found that the resulting release velocities matched the results of Cross (2004), who investigated the effects of object weights on release velocities of throws. Our data conformed to the same power law relation that captured his data. The implication was that only object weight affects release velocities, not object sizes.

To confirm this, we again performed projectile motion simulations. This time we plugged our object weights into the power law relation to generate corresponding release velocities, which we then used together with object sizes and weights and the constant
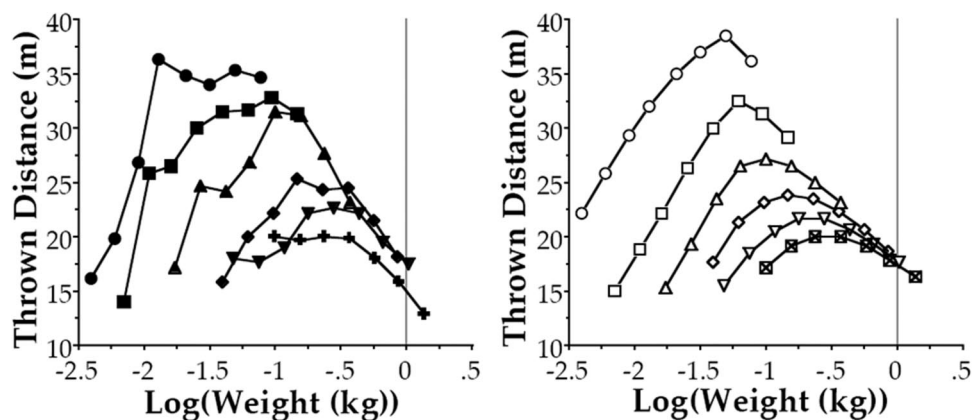

Figure 13. Mean throwing distance as a function of object size and log object weight. Left: Data from Experiment 1. Right: Data from simulations. 1-in. balls: circles; 2-in. balls: squares; 3-in. balls: triangles; 4-in. balls: diamonds; 5-in. balls: inverted triangles; 6-in. balls: crosses (i.e., from 2.5 cm to 15 cm in diameter).

24° release angle to perform simulations generating distances of throws. The resulting pattern of distances matched that found in Experiment 1, accounting for over 80% of the variance.

Most important is that this model produced exactly the size–weight relation exhibited in Experiment 1 corresponding to the maximum distance in each size. This relation was produced with no effect of object size in the dynamics of throwing. The only role of object size was in the dynamics of projectile motion. Object weight, on the other hand, played a role in both dynamics. If object size only plays a role in determining distances of throws through projectile motion and does not affect the dynamics of throwing as suggested by the results of Experiment 4, the clear implication is that the size–weight relation corresponding to optimal objects for throwing can only be known by seeing how far different objects can be thrown. The only way to apprehend the effect of size, if it acts only through the dynamics of projectile motion, is to see what happens when objects of different sizes and weights are thrown.

This last result undermines our particular smart mechanism hypothesis. Bingham et al. (1989) produced some evidence in support of the hypothesis. In particular, they showed that the grasping of different sized objects changed the stiffness of the wrist exhibited by hefting motions. Grasping bigger objects yielded a stiffer wrist. They hypothesized that heavier objects were selected in proportion to this change in stiffness to preserve the frequency of motion ($f \approx k/m$). In Experiments 2 and 3, we tested an assumption required for this smart mechanism hypothesis with results that again supported this hypothesis. The dynamics of overarm throwing is dependent on the anatomical structure of the arm and hand. If a similarity in the dynamics of hefting and throwing is to be the basis of information about throwable objects, then hefting should be performed using the arm and hand if it is to be effective in yielding information. This is what we found.

So, where do we stand? The projectile motion simulation data accounted for about 80% of the variance in the mean distance data of Experiment 1. It remains possible that some of the remaining 20% of the variance is produced by size-specific effects on throwing akin to that hypothesized and studied by Bingham et al. (1989). In this case, our smart mechanism hypothesis might still be correct. The question is how might one reveal this?

There is another way to study this smart mechanism hypothesis. One could study the learning of the affordance as people practice to acquire skilled overarm throwing. If the hypothesis is correct, then participants should be able to acquire sensitivity to the affordance by practicing only with a single set of constant density objects in which size and weight covary. Such a set of objects representing a single cut through the surface (shown in Figure 9) should be sufficient as long as the cut is not parallel to the ridge, that is, the cut should yield a curve with an optimum. This should enable learners to develop sensitivity to the information, and once they do, then it should generalize to objects in which size and weight vary independently and arbitrarily within the range of throwable objects. If this result were obtained, then given the logic described in this article, one would have to conclude that object size does affect the dynamics of throwing but that this effect is small compared with the affect of object size on projectile motion and thus it is otherwise difficult to measure. However, if the hypothesis is false and experience of knowledge of results for function learning is required, then more general experience of projectiles varying independently in size and weight will be required. We are currently testing these hypotheses.

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