HEFTING TO PERCEIVE AFFORDANCES FOR THROWING IS NOT A SMART PERCEPTUAL MECHANISM

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ABSTRACT

Bingham, Schmidt and Rosenblum (1989) found that people could, by hefting objects of different sizes, choose that of optimal weight in each size for throwing to a maximum distance. Larger weights were chosen in larger sizes as required for equivalent perceived heaviness according to the size-weight illusion. In Experiment 1, we replicated that result testing a larger range of objects and more participants. Bingham, et al. (1989) had hypothesized that hefting acts as a smart mechanism to allow objects to be perceived in the context of the dynamics of throwing. This hypothesis entails two assumptions. The first is that hefting by hand would be required to provide information about throwing by hand. We tested and confirmed this in Experiments 2 and 3. We also tested the possibility that hefting using the foot yields information about throwing using the foot. It did not. The second assumption is that optimal objects are determined solely by the dynamics of throwing. We used the mean distance of throws found in Experiment 1 together with object sizes and weights to perform simulations of projectile motion and recover release velocities. The results showed that only object weight, not size, affected throwing. This result disconfirmed the smart mechanism hypothesis. Because the affordance relation is determined in part by the dynamics of projectile motion, the conclusion is that the affordance must be learned from knowledge of results of throwing.

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

INTRODUCTION

A game commonly played by children on the beach 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. Do objects actually exhibit such an affordance for throwing? If so, are people actually able to perceive this affordance property, that is, the optimal object for throwing to a maximum distance?

Bingham, Schmidt and Rosenblum (1989) investigated these questions and found that people were well able to judge this affordance. They tested spherical objects of four different sizes (from 5cm to 12.5cm in diameter) and of 8 different weights in each size (ranging from a 4g to 700g). Participants hefted the objects and selected preferred weights for throwing in each of the 4 sizes. A week after they performed this judgment task, a subset of participants threw each of the 32 objects to a maximum distance three 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 (that is also the objects thrown the farthest) varied with the size of the objects. Greater weight was preferred for larger sizes. Bingham, et al. (1989) found that the size-weight relation for preferred objects was identical to that of the classic size-weight illusion. The illusion is that for objects of different size to be perceived of equal heaviness, the weight must actually be greater for larger objects according to a specific function. The weights selected as optimal for throwing in the 4 sizes were those that would yield equal perceived heaviness according to the size-weight illusion function. However, in this case, the perception was not illusory (that is, a misperception of weight). To the contrary, the perception was accurate and effective. It enabled throwers to successfully pick objects that best afforded maximum distance throws. How are people able to do this?

The majority of affordance studies have investigated the use of vision to perceive affordances (e.g. Bingham & Muchisky, 1993a; 1993b; 1993c; Marks, 1987; 1990; Warren, 1984; Warren & Wang, 1987), for instance, the visual perception of maximum seat height (Marks, 1990), of the maximum passable aperture (Warren & Wang, 1987), or of maximum climbable stair heights (Warren, 1984). Exceptions are studies of dynamic touch (Turvey, 1996) where, for instance, observers have been shown to be able to perceive, by wielding (without vision), the distance reachable by a hand held rod. 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 the optimal object for maximum distance throwing would seem to be different from these previously studied affordance properties because optimal throwability is inherently dynamic.[1] The affordance for throwing is composed of a functional relation between the size and weight of the objects to be thrown. Weight is a mass dimensioned dynamic property, not merely geometric. Furthermore, the maximum throwable distance is a function of the dynamics of throwing as well as the dynamics of projectile motion.

The variables that determine the distance of travel in the dynamics of projectile motion are size (that is, 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. The distance of travel only increases with increase of 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.

Bingham et al. (1989) reviewed studies of the dynamics of throwing and they revealed two essential aspects of throwing. First, energy is developed starting with more massful proximal body segments and then passed in sequence from one segment to the next proceeding distally (e.g. the trunk, then the upper arm, then the lower arm and hand). As the energy is passed from more to less massful segments, more of the energy is expressed in the velocity of motion. The joints accelerate and decelerate in a precisely timed sequence, with each successive joint reaching a significantly higher peak speed (Joris et al., 1985). Second, during the final stage of a throw (that is, the last ≈ 100ms), 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. 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. Bingham et al. (1989) 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 (or decrease) the frequency of the motion and to load the spring so as to yield high shortening velocity.

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 (that is, knowledge of results or KR) and stored in memory together with the object size and weight. Eventually, after experience of sufficient variation in sizes and weights, this information is used to induce the function specifying optimal objects.

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 meters) are not perceived accurately (Todd, 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 et al., 2002). This need to compare across occasions in different environments at widely different times is introduced by a second assumption, which is that one would have experience of throwing a variety of different weights in each given size. 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 while baseball sized apples would be encountered in an orchard and actual baseballs 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 is that hefting acts as a smart perceptual mechanism (Runeson, 1977; Bingham, et al., 1989). The idea is that the dynamics of hefting is similar to the dynamics of throwing. This is the "smartness" that would allow hefting to provide a window on the effects of object size and weight on throwing. Bingham et al. (1989) 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 (1) to develop good throwing skills and (2) to develop good sensitivity to the information provided by hefting about throwing. Specific experience of a variety of weights in given sizes would not be required. Rather, the smart mechanism would, by hypothesis, yield specification of the optimal weight in any given throwable size simply by feeling the object act in the hand as it would during throwing.

The smart mechanism hypothesis entails two assumptions that we tested in the studies reported in this paper. The first assumption is that hefting by hand would be required to provide specific information about throwing using the 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. We tested this assumption in Experiments 2 and 3. First however, we attempted in Experiment 1 to replicate the results of the hefting and throwing study done by Bingham et al (1989). They had only tested objects in four different sizes. We now tested six different sizes spanning the range of graspable objects: 1”, 2”, 3”, 4”, 5”, and 6”. Also, Bingham et al only tested throwing for 3 of the 8 participants that did the hefting. We now test 10 participants in both hefting and throwing.

The second assumption entailed by the smart mechanism hypothesis is that the optimal objects are determined by the dynamics of throwing. We used the thrown distances found in Experiment 1 together with the object sizes and weights to run simulations of projectile motion to discover the corresponding release velocities. We then use these to test the effects of object size and weight on throwing.

EXPERIMENT 1: HEFTING BY HAND FOR OVERHAND THROWING

The first experiment was performed to replicate Bingham et al. (1989) using a larger range of object sizes and weights and testing a larger number of participants. 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. Sizes were tested from 2.5cm to 15cm in diameter. 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. In the original study, 8 weights in each of 4 different sizes were hefted and only 5 weights in each size were subsequently thrown. Eight participants had been tested in hefting, but only 3 of them actually threw the objects in a subsequent session. In the current study, 8 different weights in each of 6 different sizes were tested and 10 participants both hefted and threw all of the objects. 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: .025m (1”), .050m (2”), .076m (3”), .102m (4”), .127m (5”), .152m (6”). These sizes correspond roughly to a large marble, a golf ball, a racquetball, a baseball, a softball, and a small playground ball. Weights in each size varied according to a geometric progression: $W_{n+1} = W_n$ _ 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 .127m size. To do this, a .127m 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 .025m size and .152m 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 .127m size with a weight of .048kg and the ball at .152m size with a weight of .100kg. 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.

Insert Table 1 about here

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. A 100-meter measuring tape was used to measure throwing distances.

Participants. Ten Indiana University undergraduates from the Psychology Department were paid at a rate of $8.00 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 over-arm 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 minutes and the other was throwing the objects across an outdoor field across the street from the Psychology department, lasting about 1.5 hour. They 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 anthropomorphic 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-meter 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 1st, 2nd and 3rd choice. After all weights were hefted, the participant was 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. Participants were not allowed to watch the experimenters while they were removing the eight objects of a given size from a container and arranging them on the table. The experimenter simply noted the judgments on a protocol sheet. 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. The balls were distributed randomly on the ground behind where the participant was to stand 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 over-arm and only a single step should be taken before the throw. Each participant threw the entire set of objects three times yielding a total of 141 throws (47balls x 3trials). After each set was thrown, the distances were measured and the balls were collected and redistributed on the ground behind the participant in a new random order. 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 an experimenter and read to the 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 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.

Insert Figure 1 about here

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 by .33, and third chosen weight by .16.

As we can see 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 .050m ball to the .127m ball ($p < 0.01$), while the differences between the two smallest (.025m and .050m) and two largest (.127m and .152m) 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 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 non preferred 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 their size. 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 (1st choice, 2nd choice and 3rd 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) by X (= size), by 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.

Insert Figure 2 about here

To analyze distances as a function of the participants' choices, we extrapolated choices beyond the top 3 choices: the top 3 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 4th choice, the mean of the distances for the next lightest and next heaviest to the 5th choice and so on (traveling down the arms of the inverted-U curves) for a total of 6 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 brackets.)

Insert Figure 3 about here

The polynomial regression was significant in all cases. For the .025m ball, $r^2 = .98$, $p < .01$ [$r^2 = .50$, $p < .001$]; for the .050m ball, $r^2 = .89$, $p < .05$ [$r^2 = .19$, $p < .01$]; for the .076m ball, $r^2 = .98$, $p < .01$ [$r^2 = .48$, $p < .001$]; for .102m ball, $r^2 = .98$, $p < .01$ [$r^2 = .69$, $p < .001$]; for .127m ball, $r^2 = .98$, $p < .01$ [$r^2 = .47$, $p < .001$]; and for .152m ball, $r^2 = .95$, $p < .05$ [$r^2 = .47$, $p < .001$]. The representation of the distance curves by quadratics 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 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 .025m ball; 1 for the .050m ball; 1 for the .076m ball; 1 for the .102m ball; 1 for the .127m ball; and 2 for the .152m ball. Both 1st choice (for .025m, .076m, .102m , and .127m ball) and the 2nd choice (for .050m and .152m ball) 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 Bingham et al. (1989) were replicated.

Participants were able to perceive by hefting which combinations of object size and weight were optimal for throwing an object to a maximum distance using an over-arm throw. The judgments were performed using the arm and hand to heft the objects. Bingham et al. (1989) argued that this perception was accomplished via a smart perceptual mechanism. The 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 over-arm throwing and this relation allows hefting to yield information about objects with respect to throwing. This hypothesis entails the need to heft the objects using the same limb that is able to execute the skilled over-arm 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 while 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., Masin & Crestoni, 1988; Ellis & Lederman, 1993). We now 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 over-arm throwing to a maximum. The expectation from the smart mechanism hypothesis was that participants should not be able to judge optimal objects for over-arm 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 to 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 two 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

Psychology Department were paid at a rate of $8.00 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 over-arm 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 of preferred objects for a maximum distance throw were required to be based on the use of the hand to perform an over-arm 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 non-arm/hand 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).

Insert Figure 4 about here

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-subject factor. The only main effect was size ($F_{5,\ 70} = 40.8$, $p < 0.001$). 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 ($F_{5,\ 70} = 43.5$, $p < 0.001$), and the difference between limbs became significant ($F_{1,\ 14} = 4.9$, $p < 0.05$), as well as the interaction between the limbs and size ($F_{5,\ 70} = 2.5$, $p < 0.04$).

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 suggested that hefting by non-hand limb (foot or elbow) for maximum distance over-hand 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.

Insert Figure 5 about here

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 over hand 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. However, it remains possible that the results of Experiment 2 are consistent with this hypothesis in an additional way. 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 participants to 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 be variable or noisy compared to 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 Psychology Department were paid at a rate of $8.00 per hour for participation of the two sessions of the experiment. Half of the participants were male and half were female. They were not required to have 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 over-arm 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.

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 ($F_{5, 35} = 13.2$, $p < 0.001$). 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, $p < 0.05$. In addition, the results replicated the foot hefting data from Experiment 2 by exhibiting an elevated judgment of the optimal weight as compared to Experiment 1 (see Figure 6).

Insert Figure 6 about here

An ANOVA was performed on chosen weights with size as a within-subject factor and Experiment as a between-subject factor. Comparing foot data from Experiments 2 and 3, the main effect for size was significant ($F_{5, 70} = 32.3$, $p < 0.001$), while 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 ($F_{5,70} = 27.3$, $p < 0.001$), as well as a marginal interaction between hefting limbs and size ($F_{5, 70} = 2.3$, $p < 0.06$). The reason the latter comparison was only marginally significant 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 non-hand limb hefting was much noisier and variable than hefting by hand (see Figure 7).

Insert Figure 7 about here

In Experiment 1, the 1st, 2nd and 3rd 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 (8 weights) within each size. We picked 3 tickets of paper (on which weights were listed) from a hat without replacement, and then replaced the 3 tickets and repeated the pick eight times to reproduce the data for eight 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-subject variable. While size was significant as before ($F_{5, 70} = 31.5$, $p < 0.001$ for foot hefting; $F_{5, 70} = 33.7$, $p < 0.001$ 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 ($F_{1, 14} = 5.4$, $p < 0.04$), and in that case, the interaction between size and selection method was also significant ($F_{5, 70} = 4.7$, $p < 0.001$). 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 a comparable standard deviations to 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. Since participants' judgments were not of contiguous weights, we were not able to code the 4th, 5th and 6th choice as in the previous study. We averaged the throwing distances for all not-chosen weights to compare with those of the 1st, 2nd and 3rd chosen weights (see Figure 8).

Insert Figure 8 about here

An ANOVA was performed on throwing distance with size and choice as two within-subject factors. Only size was found to be significant ($F_{5, 35} = 9.2$, $p < 0.001$). Neither choice nor its interaction with size was significant. The distance curves were flat across the choices. This finding demonstrated 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 inter-relationship between 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. Second, the maximum throwing distances of foot throwing were in general substantially shorter than hand throwing (15m vs. 35m), which indicated foot throwing was a much more difficult task compared to the over-arm throwing. Third, the ridge line of the surface, when projected on the floor, deviated from the reference line where the actual weights were equal to the preferred weights. The projected line mostly lay on the left of the reference line (4 points lay between 0 and - 0.5 on the axis), which means the actual weights being thrown to the farthest were in general lighter than expected. The foot hefting judgment tended to overestimate the optimal weight for maximum distance of foot throws.

Insert Figure 9 about here

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 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 the 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 smart mechanism. The assumption is that the same limb would have to be used for both hefting and throwing. In Experiment 2, we tested whether people can still judge the optimal weight for over-arm throwing when hefting using a limb different from the 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 considerably less than when participants used the hand. Furthermore, lighter weights than those chosen were thrown to the farthest distance. 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 (Runeson, 1977), which presumes that object size and weight effect hefting in a way similar to the effect on throwing, so that hefting can serve us a window to the effect of object size and weight on throwing. The objects selected as optimal were of increasing weight for increasing sizes. Bingham et al. (1989) 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. 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. The smart mechanism hypothesis makes specific experience of throwing a variety of weights in a given size unnecessary. One would only need to heft them.

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 velocity. The release angle is also relevant, but the optimal angle (≈36 deg) can vary fairly widely (e.g. +/– 10 deg) without much effect (Parker, 1977). If both size and weight affect the dynamics of throwing, then the effect should be apparent in variations in release velocities. Previous studies of throwing have shown that object weight does affect release velocity (e.g. Cross, 2004), but there are no studies of the effect of object size on release velocity. We used our data to investigate this question. We used the mean throw distances found in Experiment 1 together with the object sizes and weights to perform simulations of projectile motion to discover the corresponding release velocities. We then used them to examine the influence of object size and weight on the throwing performance.

For a projectile with air resistance and quadratic drag, the following parameters are considered in predicting the distance of travel: the projectile's mass (*m*) and the cross-sectional area (*A*), release angle (_), release velocity (*V*), and the drag coefficient (*CD*). With the available weights (*m*), sizes (*A*) and thrown distances in the Experiment 1, we only needed the release angle (_) and the drag coefficient (*CD*) to recover the release velocities. According to Parker (1977), the appropriate drag coefficient (*CD*) for our spheres and velocities of travel is 0.5, and for any maximum horizontal projection, a release angle (_) of 36° above the horizontal is necessary. So, we used these values to discover the corresponding release velocities for each throw by also plugging the weights and sizes into the equations for projectile motion and varying the initial velocities to find those required to generate the throw distances.

The simulated thrown distances using the recovered release velocities accounted for 99.4% of the variance of the actual distance data ($r^2 = .99$, $F_{1, 46} = 7286.7$, $p < .001$). We found that release velocity followed a function of object weight: as object weight increased, the release velocity decreased. However, velocities did not decrease until the object weight reached .05kg (log weight = −1.30, see Figure 10). A separate linear regression analysis was performed on the data lying on each side of a weight value at .05kg. For weights less than .05kg, the linear regression of weight on velocity was not significant ($r^2 = .06$, $F_{1, 16} = 0.9$, $p > .05$), and the mean velocity was 22m/s. However, for weights greater than .05kg, the linear regression was significant ($r^2 = 0.83$, $F_{1, 29} = 134.9$, $p < .001$), with a negative slope (Velocity = – 6.0 _ Log weight + 13.1). We transformed the regression function to a power law: Velocity = 13.3 _ $(\text{Weight})^{-0.15}$. These findings replicated 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 .05kg, the release velocity followed a power function of weight with an exponent of – 0.15. Below .05kg, the weight did not affect release velocities, which were constant at the maximum release velocity of about 20m/s.

Insert Figure 10 about here

This functional dependence of release velocity on weight, but not on size implied that only weight affects the dynamics of throwing, but 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 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 .05kg, we used a constant velocity of 20m/s. For objects heavier than .05kg, we used a set of velocities generated by the negative power function. The result reproduced our distance data remarkably well, accounting for 82% of the variance (r^2 = .82, $F_{1, 46}$ = 210.5, p < .001, see Figure 11). The resulting regression function was: Mean throw distance = .97 _ simulated distance + 1.33. Additionally, the simulated distances exhibited the same effect 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 increasing object size (see Figure 12).

Insert Figures 11 and 12 about here

CONCLUSIONS

In common experience at the beach, for instance, it seems that people are able to pick the optimally sized and weighted stone for throwing to a maximum distance. Bingham, et al. (1989) investigated whether people are actually able to perceive this affordance property and in our Experiment 1, we replicated their result showing that people can indeed select the optimal weight for different sized spherical objects to be thrown to a maximum distance. The original result was surprising because different weights were optimal in different sizes. The ability to select appropriate weights for different sized objects surpassed what would be required to pick the best throwing stone on the beach where the ability to simply pick the best weight would be sufficient. Given the fact that size and weight tend to co-vary among objects available in natural environments, like stones on the beach or apples in an orchard, how would people obtain the experience necessary to become familiar with a relational property defined over independent variations in both size and weight?

This problem inspired Bingham, et al. (1989) to hypothesize that the affordance relation was perceived via a smart mechanism. They produced some evidence to support this hypothesis. In Experiments 2 and 3, we tested an assumption required for this smart mechanism hypothesis with results that supported the hypothesis. However, we next tested the hypothesis by using the throwing distance data and the object sizes and weights to perform simulations of projectile motion and derive estimates of the release velocities. The smart mechanism hypothesis requires that both size and weight affect throwing and thus, the release velocities. We found that only weight variations affect throwing and that size contributes to a determination of distance of throws only through the dynamics of projectile motion. This disconfirms the smart mechanism hypothesis about how hefting could enable people to perceive the affordance of objects for maximum distance throws. The only way people could come to appreciate the contribution of object size to a determination of throwing distance for objects of different weights is by seeing how far they were able to throw different objects that varied in both weight and size. The ability to perceive the affordance must be acquired through extensive throwing experience yielding knowledge of results (KR). This conclusion is a very surprising, but undeniable, implication of our results.

The other conclusion is that the perception also depends on the use of the skilled throwing limb. That is, as much as skilled throwing is specific to a given limb, so is the ability to perceive the optimal object for throwing using that limb. In the context of the first conclusion, this second conclusion is also bit surprising. Visually experienced KR apparently becomes invested in the task specific hefting ability of a limb.

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FOOTNOTES

1. 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.

TABLES

Table 1: Object Weights Within Size

Diameter(m)	Object weight (kg)							
.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	N/A

FIGURE CAPTIONS

Figure 1. Mean of chosen weights selected by participants as a function of size in Experiment 1 (filled diamonds) and the original study in 1989 (stars) (Weight in kilograms, Size by radius in inches).

Figure 2. A Surface representing a distance function of two variables: size and weight in Experiment 1. (Distance in meters, Size by radius in inches, and log weight in dimensionless units = actual weights divided by the mean chosen 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 is thrown to the farthest distance.

Figure 3. The mean thrown distance as a function of size and preference. Distances are in meters. Preferences are ranked by choices from “1” to “6”: 1 represents the most preferred object, 6 represents the least preferred object. Sizes are by radius in inches: 1’’ ball (filled circles), 2’’ ball (open circles), 3’’ ball (filled squares), 4’’ ball (open squares), 5’’ ball (filled triangles), and 6’’ ball (open triangles). The curves represent best fit quadratic regression.

Figure 4. Mean of weights selected by participants as a function of size in Experiments 1 and 2. Hefting using a hand is represented by filled diamonds,

hefting using a foot is represented by filled triangles, and hefting using an elbow is represented by filled squares (Weight in kilograms, Size by radius in inches).

Figure 5. Standard deviation of the chosen weight as a function of size in Experiments 1 and 2. Hefting using a hand is represented by filled diamonds, hefting using a foot is represented by filled triangles, and hefting using an elbow is represented by filled squares (Weight in kilograms, Size by radius in inches).

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, and hefting using a foot in Experiment 3 is represented by filled squares. The mean of weights chosen randomly is represented by stars (Weight in kilograms, Size by radius in inches).

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, and hefting using a foot in Experiment 3 is represented by filled squares. The standard deviation of chosen randomly is represented by stars (Weight in

kilograms, Size by radius in inches).

Figure 8. The mean thrown distance in Experiment 3 as a function of size and preference. Distances are in meters. Preferences are ranked as “1”, “2”, “3”, and “not chosen”: “1” represents the most preferred object, “not chosen” represents those not preferred object. Sizes are by radius in inches: 1’’ ball (filled diamonds), 2’’ ball (filled squares), 3’’ ball (filled triangles), 4’’ ball (crosses), 5’’ ball (stars), and 6’’ ball (filled circles).

Figure 9. A surface representing a distance function of two variables, size and weight in Experiment 3. (Distance in meters, Size by radius in inches, and Weight in log of actual weights divided by the mean chosen 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 is thrown to the farthest distance.

Figure 10. The recovered release velocities as a function of 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 (R2 = 0.06), while the linear regression on the right side of the reference line shows

strong negative correlation between release velocity and object weight ($R2 = 0.83$).

Figure 11. The correlation between the simulated thrown distances and the thrown distances in Experiment 1. Simulated distances were generated using power law relation between weight and release velocity for weights greater than 0.05 kg, and a constant release velocity of 20 m/s for weights below 0.05 kg. The linear regression shows significant correlation ($r2 = .82$, $F\ 1, 46 = 210.5$, $p < .001$).

Figure 12. Mean throwing distance as a function of object weight and. Figure A displays the data from Experiment 1, and Figure B displays the data from simulations. (Distance in meters, Size by radius in inches, and Weight in Logarithmic of kilograms)

Figure 1

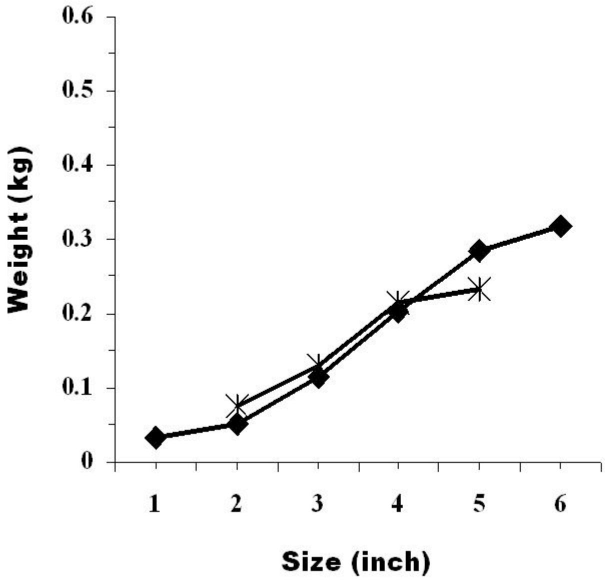


Figure 2

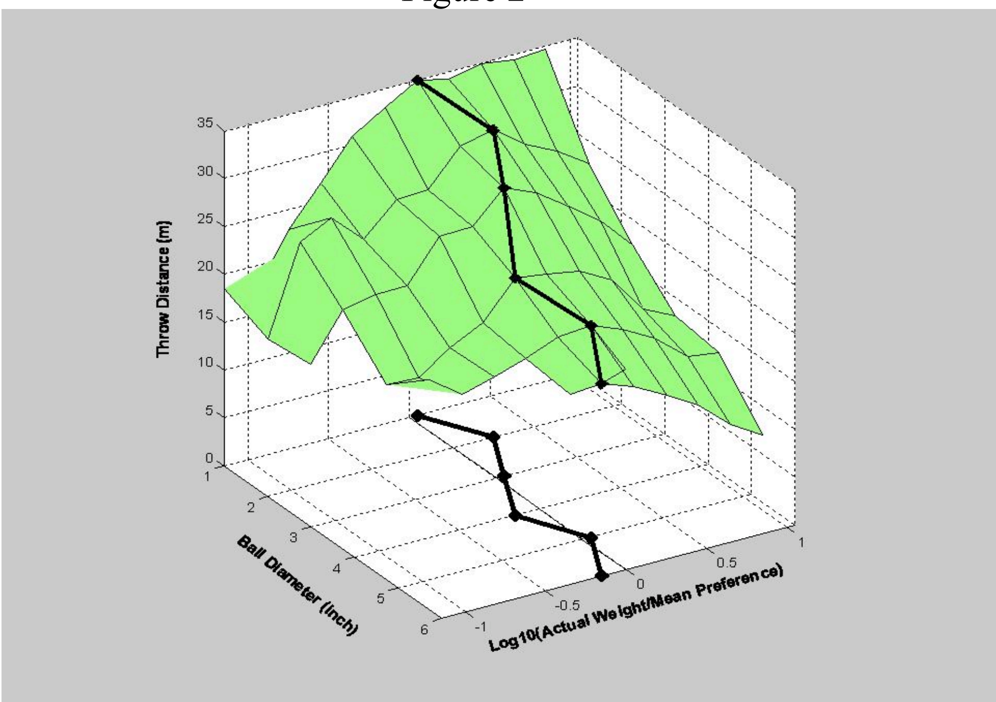


Figure 3

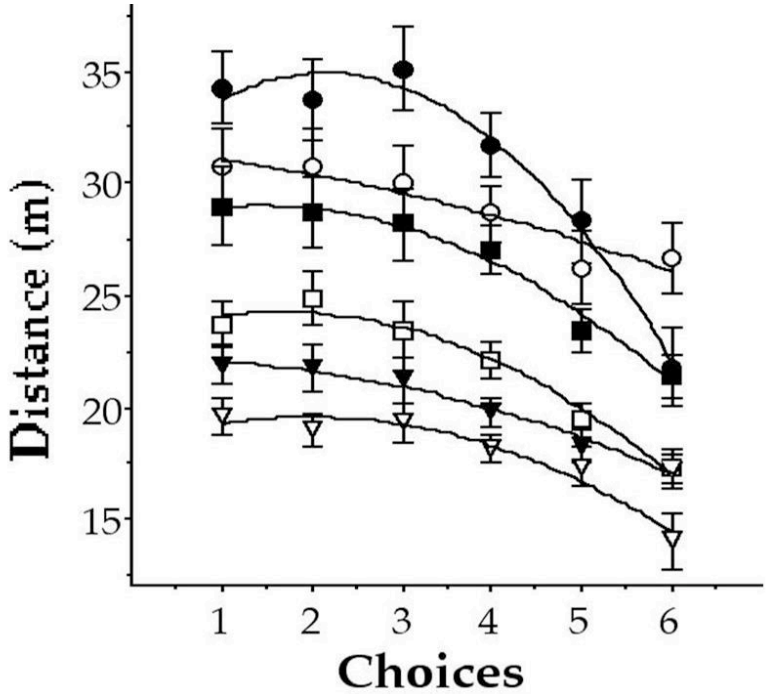


Figure 4

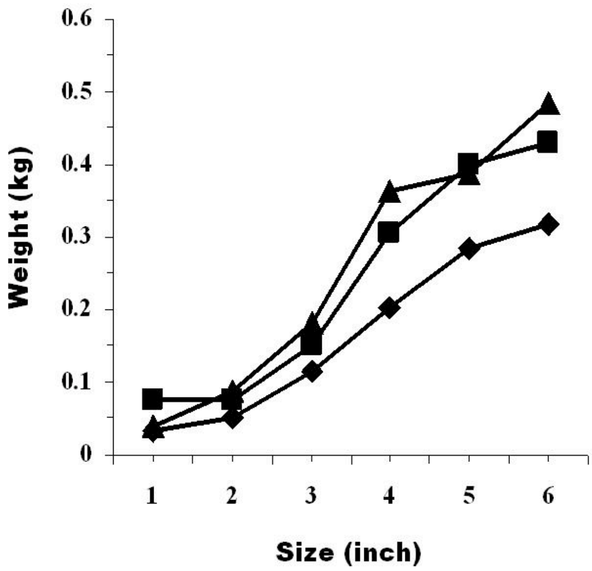
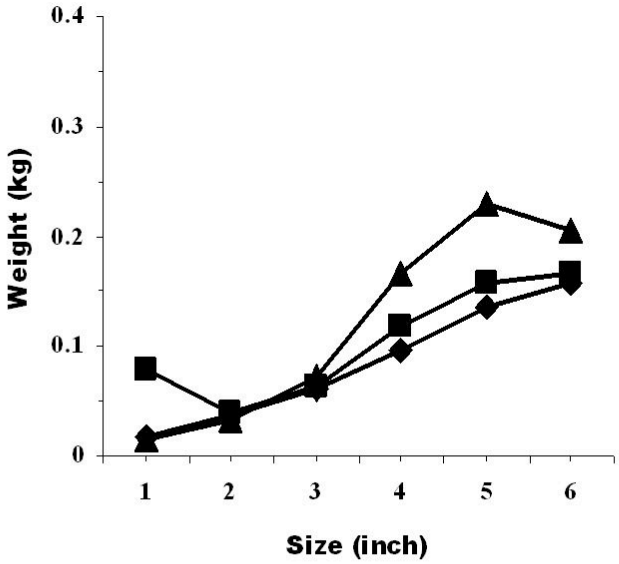


Figure 5



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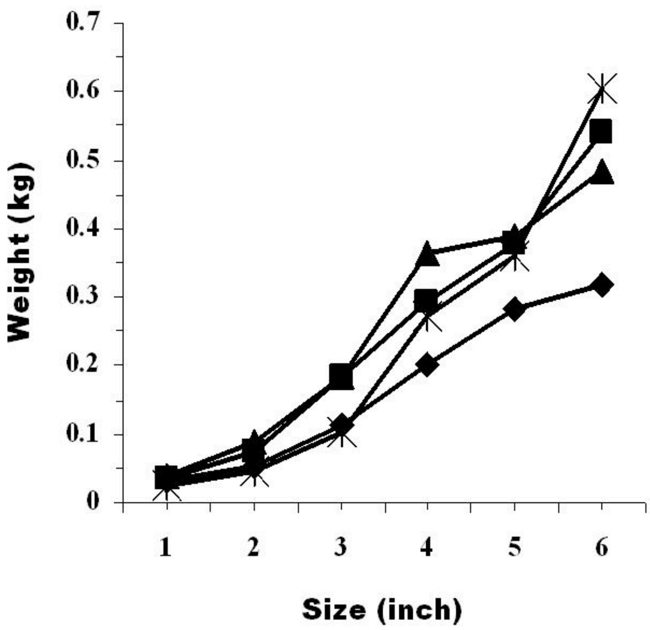

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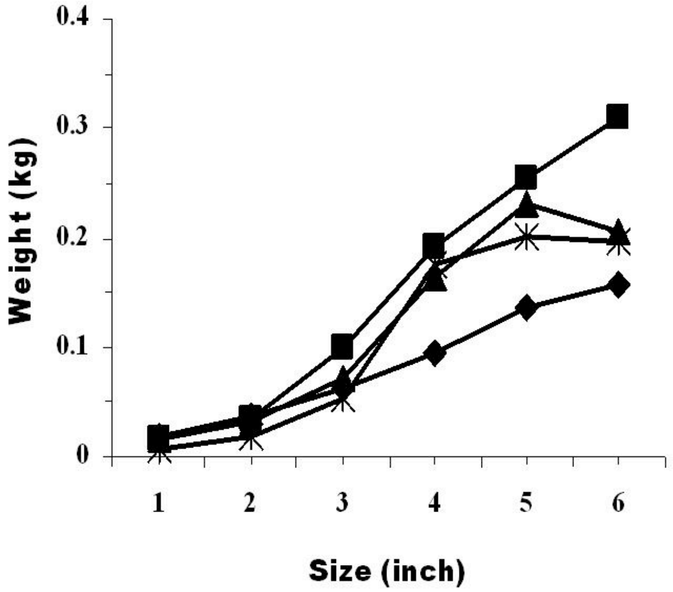

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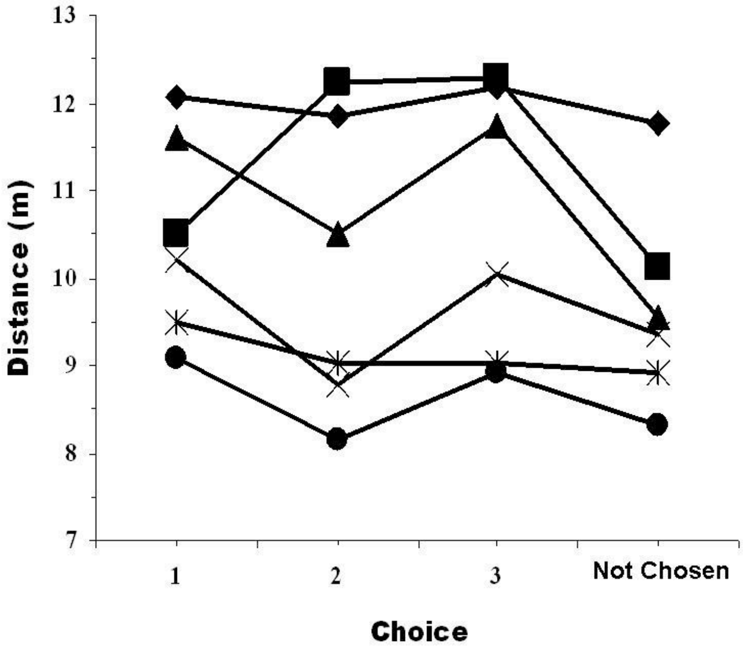


Figure 9

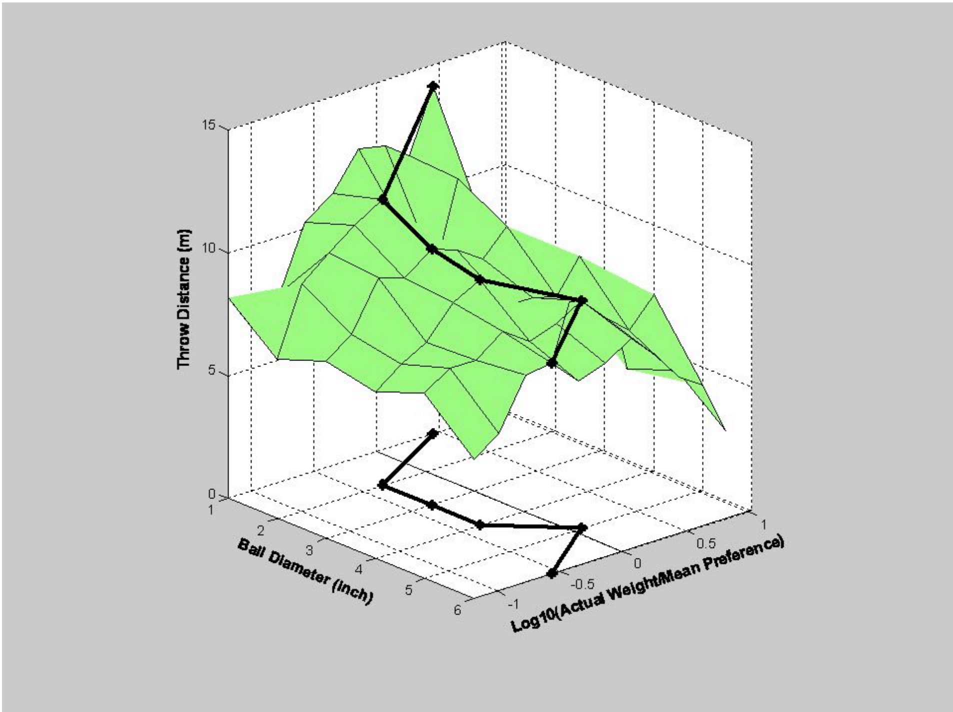
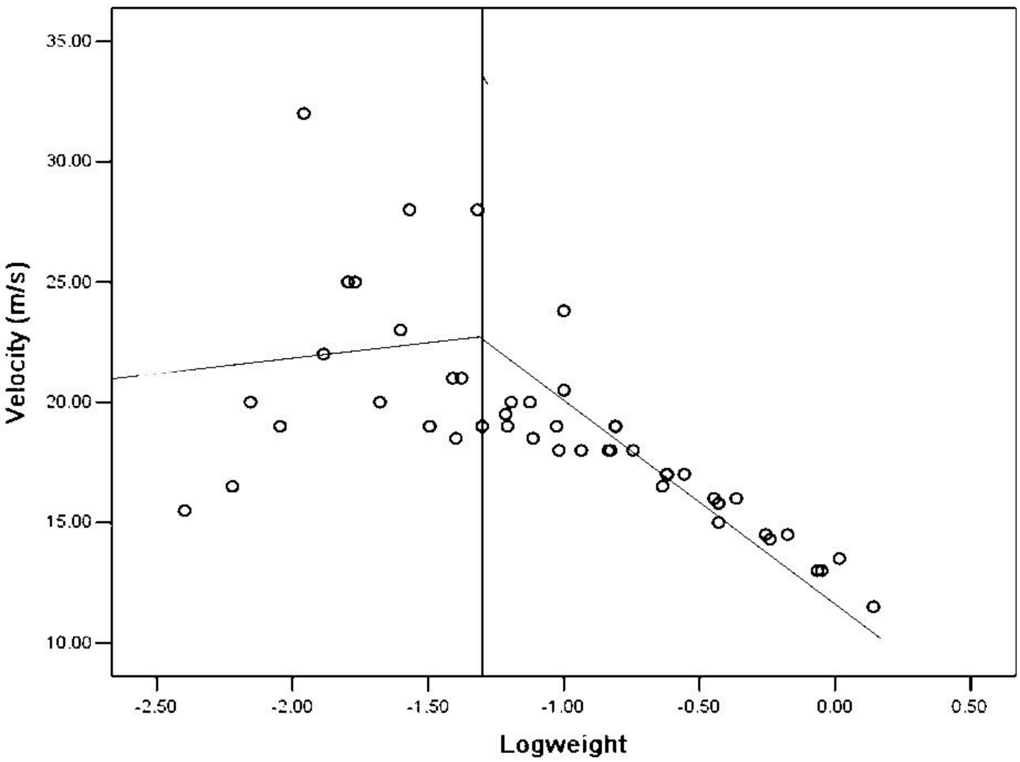


Figure 10


35.00
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Velocity (m/s)
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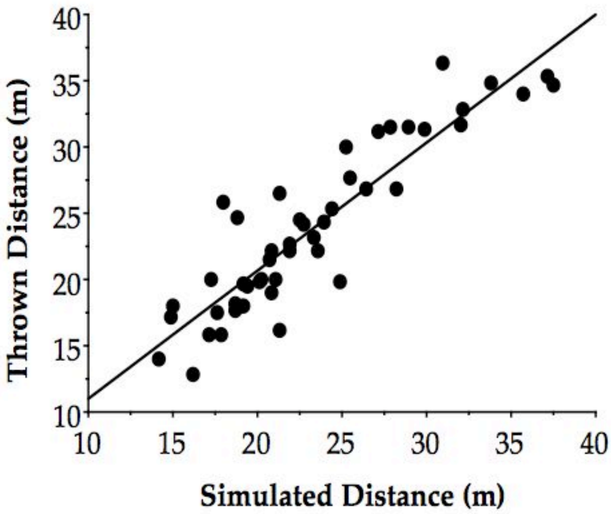
Logweight

Figure 11


40
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Thrown Distance (m)
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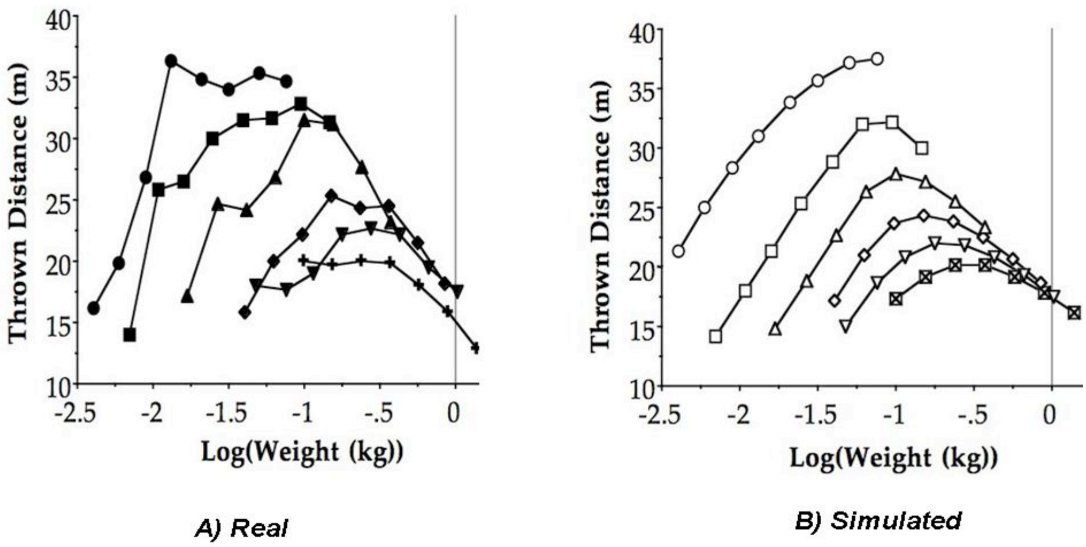
Simulated Distance (m)

Figure 12


Thrown Distance (m)
Log(Weight (kg))
A) Real
Thrown Distance (m)
Log(Weight (kg))
B) Simulated