

Learning To Perceive the Affordance for Long-Distance Throwing: Smart Mechanism or Function Learning?

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Bingham, Schmidt, & Rosenblum, (1989) showed that people are able to select, by hefting balls, the optimal weight for each size ball to be thrown farthest. We now investigate function learning and smart mechanisms as hypotheses about how this affordance is perceived. Twenty-four unskilled adult throwers learned to throw by practicing with a subset of balls that would only allow acquisition of the ability to perceive the affordance if hefting acts as a smart mechanism to provide access to a single information variable that specifies the affordance. Participants hefted 48 balls of different sizes and weights and judged throwability. Then, participants, assigned to one of four groups, practiced throwing (three groups with vision and one without) for a month using different subsets of balls. Finally, hefting and throwing were tested again with all the balls. The results showed: (1) inability to detect throwability before practice, (2) throwing improved with practice, and (3) participants learned to perceive the affordance, but only with visual feedback. These results indicated that the affordance is perceived using a smart mechanism acquired while learning to throw.

Keywords: affordance, throwing, perceptual learning, motor learning

A common scenario at the beach is that children compete in throwing to see who can throw stones to the farthest distance out on the water. Part of the game is to select the optimal stone for throwing to a maximum distance. Assuming a roughly spherical shape, stones are selected depending on their relative size and weight. Bingham, Schmidt, and Rosenblum (1989) investigated whether adults are actually able to perceive this affordance property, namely, the optimal weight for each graspable ball size to be thrown to a maximum distance. First, Bingham et al. asked participants to heft balls in each of four different sizes and to select the weight in each size that they could throw the farthest. Participants selected weights that increased with ball size. A week after the hefting task, the participants returned to throw each of the balls to the farthest distance that they could achieve. The result was that the balls that had been selected as optimal were thrown the farthest (the balls were not labeled in any way that would allow participants to remember or recognize their choices, except of course by feeling them once again). Distances for each ball size varied as an inverted-U-shaped function of ball weight with the maxima of the functions corresponding to the selected weights. The curves for the different ball sizes (one curve per size) were ordered by size with the smallest balls traveling to the largest distances and the peaks of the curves shifting up the weight axis with increasing ball size. (see

Figure 1). These results were recently replicated by Zhu and Bingham (2008) with a larger range of ball sizes and weights. Thus, people are indeed able to perceive this affordance for throwability.

Affordances are complex dispositional properties of objects (Gibson, 1979; Turvey, Shaw, Reed, & Mace, 1981) that are relevant to potential actions performed by a perceiver and that are perceptible. Optimal throwability is an exemplary instance. The property is composed of a relation between the size and weight of graspable and throwable objects. The only way for the affordance to be manifest is in the context of the relevant action, namely, maximum distance throwing. The results of the judgment studies showed that the affordance was perceptible, but the question is how?

Bingham et al. (1989) had proposed that this affordance is perceived via a “smart” perceptual mechanism. According to Runeson (1977), perception might be smart by taking advantage of particular circumstances in a task that simplify the perceptual problems by providing access to a single information variable that specifies the perceived property. The application of this idea by Bingham et al. to perceiving the affordance for throwing was to hypothesize that hefting acts as a smart perceptual mechanism to provide a window on the effect of ball size and weight on throwing. The “smartness” entailed two assumptions. The first assumption was that ball size and weight both affect distances of throws by affecting the throwing itself. The second assumption was that the dynamics of hefting should be similar to the dynamics of throwing. The combined assumptions implied that ball size and weight would affect both hefting and throwing motions in similar ways to yield a single information variable detectible by hefting. Bingham et al. (1989) reviewed the dynamics of throwing and found that throwing entailed transfer of high energy from the trunk to the hand via the long tendons of the wrist, and these tendons are also used in the control of finger flexion during hefting. Hence,

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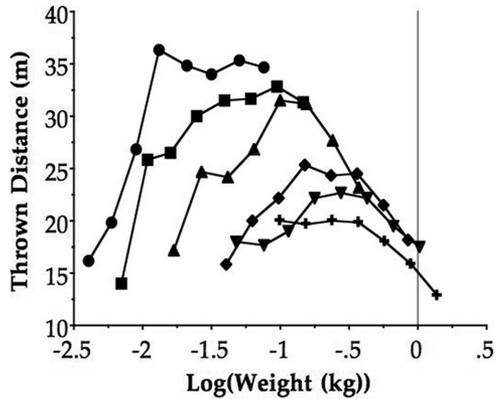


Figure 1. Illustration of the results from previous studies. Mean distances of throws from Experiment 1 of Zhu and Bingham (2008). Object diameters: 1" (circles); 2" (squares); 3" (upright triangles); 4" (diamonds); 5" (inverted triangles); and 6" (crosses). See text for additional explanation.

hefting motions involving the tendons at the wrist might provide perceptual information about throwing. They performed an experiment to measure the effect of grasped ball size on stiffness at the wrist, and found increases in stiffness with increasing ball size as expected. Grasping larger balls changes the lengths of the tendons and muscles and thus, the joint stiffness. Accordingly, they hypothesized that greater mass was required for larger balls to preserve both the frequency of the motion at the wrist and the relative timing among the shoulder, elbow, and wrist joints when throwing. Balls selected by hefting as optimal for throwing increase in mass as ball size increases (Bingham et al., 1989; Zhu & Bingham, 2008). The idea was that the frequency response in hefting provided the information.

Zhu and Bingham (2008) used simulation of projectile motion dynamics to investigate the first assumption entailed by this particular smart mechanism hypothesis, namely, that ball size and weight both affect throwing and that it is this that yields the specific variations in distances of throws. Throwing and projectile motion are connected by two variables, the release angle and the release velocity of throws. Thus, the assumption is that ball size and weight both affect these variables. Zhu and Bingham tested skilled throwers and found that release angles did not vary with either ball size or ball weight. Using the mean release angle found in this study together with the distances of throws and ball sizes and weights from the original study, Zhu and Bingham performed simulations of projectile motion to derive release velocities. They found that release velocity changed systematically with ball weight, but not with ball size. The functional relationship between the release velocity and ball weight was described and used together with ball sizes and weights and projectile motion dynamics to predict throwing distances. The simulated distances accounted for over 80% of the variance in the actual measured distances. These results demonstrated that ball size only plays a role in the dynamics of projectile motion (affecting the air resistance), and has no affect on throwing per se. This undermined the particular smart perceptual mechanism hypothesis proposed by Bingham et al. (1989).

Zhu and Bingham (2008) considered alternatives to smart mechanisms and hypothesized that the affordance could also be per-

ceived through learning a single valued function (throwing distance) of two variables (ball size and weight). Function learning is an active research area in psychology (McDaniel & Busemeyer, 2005; DeLosh, Busemeyer, & McDaniel, 1997), according to which, people can learn a function by sampling inputs repetitively within a certain stimulus range when knowledge of results is provided. Once the function is learned, people are able to predict the outcome of a given input that falls either within (interpolation) or beyond (extrapolation) the range of experienced stimuli. In this view, perception of the affordance would entail the prediction of throwing distance based on the inputs of ball size and weight according to the functional relation between them. The function serves as a kind of lookup table, for which the simultaneous perception of multiple variables, in this case object size and object weight, would be required.

However, learning this function would not be easy, because it entails learning a curvilinear function based on two independent inputs. Variation of the first variable, weight, yields an inverted-U-shaped curve while variation of the second variable, size, yields variation in those weight-dependent curves. As a function of size, the curves shift in height, curvature and location along the weight axis. Learning this entire function would require an independent and adequate sampling of both input variables. Exposure to values of the function generated only by variations in weight or only by variations in size or, finally, only by a single covariation of size and weight would not allow learning of the entire function (see Figure 2). The function can be represented as a surface. The sampling of a single slice through this surface would be insufficient to yield the entire surface. Although function learning does entail the possibility of extrapolation beyond sampled data, such extrapolation requires more than a single sample point. A single

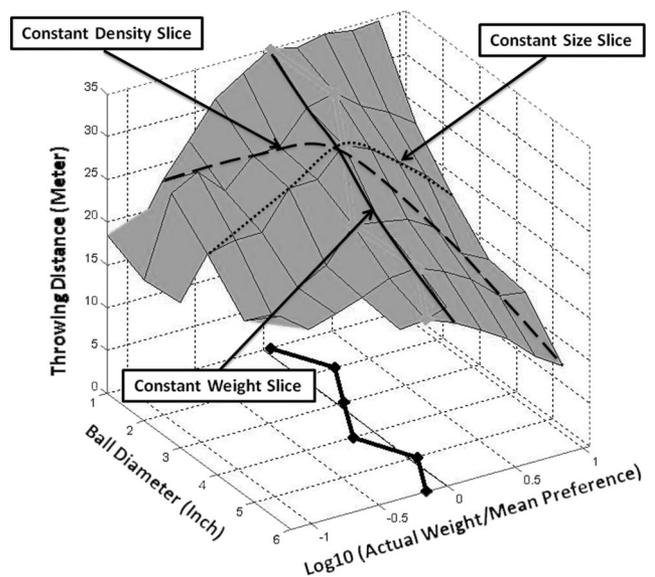


Figure 2. Illustration of various slices through the size-weight-distance surface including a constant size slice, a constant weight slice, and a constant density slice. The Figure also illustrates both the throwing performance and perceptual ability of skilled throwers in Zhu and Bingham (2008). See Figure 3 and accompanying text for explanation of how this Figure was constructed from the data.

slice yields only one sample point in directions other than along the slice itself and thus, does not allow extrapolation in those directions to access the full surface.

On the other hand, if perception of the affordance was achieved using a smart mechanism that entails a single information variable that specifies throwability, then that information could be learned with sampling of the two variables restricted to a single slice through the space. Enough variation in sampling would be required only to become sensitive to the information provided by the smart mechanism. That sensitivity would then generalize to the entire space. So, for instance, sampling the effect of weight variation in a single ball size would yield the inverted-U-shaped variation in resulting distances of throws and this should be enough to become sensitive to the information specifying those potential distances. Once the information can be detected, it can be used to perceive the function at all ball sizes and weights. Of course, such a smart mechanism would have to be different from the one originally proposed by Bingham et al. (1989) (because the evidence has failed to support it). Another different smart mechanism remains possible nevertheless.

In the current study, we investigated whether perception of the affordance is achieved by certain smart mechanism (yielding a single effective information variable) or instead, is achieved as a result of learning a function of multiple perceptual variables. We tested this by training unskilled participants to throw long distance, during which they also learned to perceive the affordance. We restricted their sampling of the size, weight, and distance space so that they would be prevented from learning the affordance if such learning is achieved by function learning. Participants were allowed to sample weight variation in a given size, or size variation at a given weight level, or simultaneous covariation of size and weight (along a single slice through the space in Figure 2). If after any of these experiences, the affordance was generally perceptible, that is, over the entire space, then some version of the smart mechanism hypothesis would be supported. If, on the other hand, only the balls that had been experienced during practice could be judged correctly, then the function learning hypothesis would be supported.

Vision is not essential to the task of perceiving the affordance for throwing. People can perform both hefting and throwing without seeing the ball, and they can perceive the affordance for throwing well in this way. Nevertheless, it is unclear whether vision would be required to acquire the ability to perceive the affordance. We expect the affordance for throwing to be acquired while learning to throw. Presumably, distances of throws would have to be visually perceived as part of the process of acquiring the ability to perceive the affordance, but it is possible that one might be able to apprehend distances of throws using somatosensation without vision. We tested this possibility by asking one group of participants to practice throwing without vision of the resulting distances of throws. If they failed to learn the affordance, then two related conclusions could be drawn. First, visual perception of distances of throws is required to learn the affordance. Second, learning to throw is a not sufficient condition for learning to perceive the affordance.

The current study tackled three questions: first, whether the acquisition of the ability to perceive the affordance for maximum distance of throws was coupled with the acquisition of skill for long distance throwing; second, whether the affordance was per-

ceived via a smart perceptual mechanism (and thus, one information variable) or instead involved a learned (associative) function (one relating distance of throw to perceived ball size and perceived ball weight); and third, whether visual perception of distances of throws is important for acquisition of the ability to perceive the affordance for throwing and thus, whether learning to throw was a sufficient condition for learning to perceive the affordance.

To answer the first question, we recruited and trained unskilled throwers to throw. Perceptual judgments of the affordance were assessed before and after training to test if perceptual judgments became accurate only with the acquisition of throwing skill after practice. To answer the second question, we manipulated the set of practice balls thrown during training. Three configurations of size and weight were used: a set of balls of constant weight varying in size; a set of balls of constant size varying in weight; and a set of balls of constant density with covariation of size and weight (see Figure 2). If perception of the affordance were acquired through function learning, practice with different sets of balls should yield different learning about the function. Specifically, the Constant Size Group should be able to pick the optimal weight in the experienced size, but not in other sizes, in which the optimal weight is different. The Constant Weight Group should not be able to pick the optimal weight in any size, although they should be able to pick the optimal size, and the Constant Density Group should be able to pick the optimal ball in the constant density set, but not the optimal weight in any given size. In contrast, if the smart perceptual mechanism hypothesis is correct, using any set of balls for practice would be sufficient to yield a generalized sensitivity to the information that specifies the optimally weighted ball at any given size for maximum distance throwing. Last, to answer the third question, we manipulated the availability of vision before, during, and after practice. Using the same balls, one group of participants was asked to throw balls with vision during and after practice, and the other group to throw without vision during practice but with vision after practice. If visual perception of throwing distance was important for acquisition of the ability to perceive the affordance, differences in the judgments should be expected between the two groups after practice, and the no-vision group might improve in judgment ability when vision was provided after practice.

Method

Apparatus

Forty-eight spherical balls were made with eight weights in each of six sizes. Balls varied in size with diameters as follows: 2.54 cm (1"), 5.08 cm (2"), 7.62 cm (3"), 10.16 cm (4"), 12.7 cm (5"), and 15.24 cm (6"). These sizes correspond roughly to a small marble, a golf ball, a baseball, a soft ball, a playground ball, and a water polo ball. Weights in each size varied as a geometric progression: $W_{n+1} = W_n \times 1.55$. Eight weights were generated in each of the six sizes, starting with the lightest weight that could be constructed in each size. The matrix of ball size and weight was constructed so that three subsets of balls were residing in the matrix: a set of six balls at a constant weight of 69g (varying therefore only in size); a set of six balls at a constant density (.3 g/cm³); and a set of six balls at a constant size of 7.62 cm in diameter. For purpose of

Table 1
Configuration of Ball Size and Weight

Diameters (in/cm)				Object weight (g)				
1"/2.54 cm	<u>3.2</u>	5.0	7.7	11.9	18.5	28.6	44.4	68.8
2"/5.08 cm	7.7	11.9	<u>18.5</u>	28.7	44.4	68.9	106.8	165.5
3"/7.62 cm	18.5	28.7	<i>44.4</i>	<u>68.9</u>	<i>106.8</i>	<i>165.5</i>	256.5	397.6
4"/10.16 cm	29.0	45.0	69.7	108.0	<u>167.4</u>	259.5	402.2	623.3
5"/12.70 cm	45.0	69.8	108.1	167.6	259.7	<u>402.6</u>	624.0	967.2
6"/15.24 cm	69.0	107.0	165.8	256.9	398.3	<u>617.3</u>	956.8	1483.1

Note. **Bold** figures denotes the constant weight subset. *Italic* figures denote the constant size subset. Underscored figures denote the constant density subset.

minimizing the possible function learning, only one ball was shared by all three subsets (see Table 1).

Spherical plastic 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 12.7 cm size. To do this, a 12.7-cm 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 2.54 cm size and 15.24 cm size, we used commercially available hollow steel balls instead of plastic shells. Finally, some of the lightest balls were pure Styrofoam, such as the ball at 12.7 cm size with a weight of 45 g and the ball at 15.24 cm size with a weight of 69 g. 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 adhesive tape to produce good graspability and improved durability. To prevent balls from being remembered by participants in the later hefting and throwing task, each ball was painted yellow to create identical appearance and surface texture, and then coded with a sign that was only recognizable to experimenters. The yellow look also increased the visibility of the ball in videos taped during throwing sessions.

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. The wire 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. For the smallest sizes, layers of duct tape were used to coat the surface of the ball so that the desired weights could be achieved.

To measure the throwing distances accurately, we used a measuring tape (100 m long) at distances shorter than ten meters, and a laser rangefinder (Simmons Yardage Master 1000, Simmons Outdoor Corporation, Overland Park, KS, USA) at distances longer than 10 m.

Participants

Twenty-four Indiana University undergraduate students were recruited for the experiments. They passed a screening session to

participate in the experiment (see the screening procedure). Only one participant was male and the rest were all females. Participants were required to be capable of throwing balls and to have had little prior experience or skill at over-arm throwing, to have good (corrected) vision, and to be free of motor impairments. They were paid at a rate of \$9.00 per hour for participation in the testing of hefting judgments and throwing performance.

Experimental Procedure

Experiments involved assessing hefting judgments and throwing performance before, during, and after practice (see Table 2).

Screening participants. First, a screening procedure was used to select participants. Potential participants were asked to throw, using their dominant hand, three tennis balls to a maximum distance in an outdoor field. The mean throwing distance was calculated to determine the eligibility for participation. Only participants who met the criterion of being unskilled throwers were recruited. The criterion was defined as throwing a tennis ball to a distance equal to or less than two standard deviations (6.5 m) below the mean of throwing distance (29 m) achieved by normally skilled throwers (hence distance ≤ 16 m, according to Zhu and Bingham, 2008).¹ Participants who did not meet the criterion were thanked for their interest and asked to withdraw from the experiment.

Initial test of hefting judgment. Subsequently, the recruited participants were tested in the hefting task. The anthropometric data (gender, height, weight, arm length, and hand span) were measured and recorded before hefting judgments were assessed. For the hefting task, participants were asked to sit in front of a table. An experimenter sat behind the table and placed a set of eight balls of a given size on the table. The balls were arranged in a random weight order. Participants were asked to lift (using the dominant hand) each of the balls in turn to feel its weight and judge its throwability. After participants had lifted and felt all the balls of a given size, they were asked to choose the best balls for throwing to a maximum distance. Participants were asked to choose the best three balls in order, namely, best, next best, and third best, and indicate their choices by pointing. They were asked to judge six different sets (sizes) of balls, each including eight different weights.

Initial test of throwing distance. Following the hefting judgment, participants were led to a playing field where they were asked

¹ It was found later that the mean throwing distance of three tennis ball throws from the recruited participants was 13.25 ± 2.99 m.

Table 2
Experimental Procedure Diagram

Initial test		Throwing ability test						10 min	
		Hefting test w/all objects						0.5 hr	
		Throwing test w/all objects						1 hr	
		Monday	Tuesday	Wednesday	Thursday	Friday	Saturday		
A month practice	Week 1	Test w/subset & Instructional practice	Rest	Instructional practice	Rest	Instructional practice	Rest	Test \approx 2.5 hr	
	Week 2	Test w/subset & Instructional practice	Rest	Instructional practice	Rest	Instructional practice	Rest	(35 min \times 4 days)	
	Week 3	Test w/subset & Instructional practice	Rest	Instructional practice	Rest	Instructional practice	Rest	Practice = 12 hr	
	Week 4	Test w/subset & Instructional practice	Rest	Instructional practice	Rest	Instructional practice	Rest	(1 hr \times 12 days)	
Final test		Hefting test w/all objects						Test = 2 hr	
		Throwing test w/all objects						(0.5 hr \times 2 tests +	
		Hefting test w/all objects						1 hr)	

to throw each ball from the entire set of balls to a maximum distance three times using their dominant hand. Participants were blindfolded and were handed the balls for throwing. They were also encouraged to do some stretching and warm-up throws before the throwing, and if fatigue was felt during the test, a rest was taken. Balls from the entire set were all thrown in a random order and then the set was repeated twice more each time using a new random order. The distance of each throw was measured and recorded.

Practice of throwing. When initial tests of hefting and throwing were completed, participants were scheduled for a month-long practice of throwing. They were randomly assigned to one of four groups.² Each of three groups practiced with a different subset of the balls (constant size, constant weight, or constant density). Three groups threw the given subsets of balls with vision, but a fourth group was asked to throw the constant density subset without vision during practice. They wore a blindfold when performing maximum distance throws. According to Van Den Tillaar (2004), an effective training program for generating fast throws should incorporate training three times per week for 5 weeks, using underweight balls or in combination with overweight balls. We trained participants three times a week for 4 weeks, and used two types of balls for practice: a subset of six balls with variation of size or/and weight, and a tennis ball.³ During practice with the subset of balls, participants threw each of the balls in a random order to a maximum distance in a field four times, and they were encouraged to explore the relationship between the balls and throwing distances. This practice took place on Monday of each practice week, and it was videotaped for later motion analysis. To motivate participants' effort for improvement, a competitive prize of \$20 was offered to award the most improved thrower. The mean distance of throws was calculated each week for each of the participants and ranked for all of the participants. By the end of practice, the participant whose mean throwing distance increased the most received the award. In addition to throwing balls, participants also threw a tennis ball in a gym for practice, during which the tennis ball was first thrown against a wall by throwers, and then thrown back and forth between a thrower and a throwing expert, with the distance between them being increased gradually. Participants were given instructions about how to enhance the coordination of movement at the hip, shoulder, elbow, and wrist by stepping forward with the contralateral foot, as well as on the time at which the ball should be released (when arm speed

achieved maximal value). This practice lasted for an hour and took place on three separate days each week (Monday, Wednesday, and Friday), and participants were instructed to do no other throwing practice with other objects during the month. At the end of practice, participants were asked to judge the most throwable ball from the subset of six balls in order by pointing out their best three choices.

Final tests of hefting and throwing. A week after the practice sessions, participants were tested again in the hefting task and throwing using the whole set of balls. They were first tested in the hefting, and then led to the outdoor field to do the throwing task. Different from the earlier test, all participants were allowed to see how far each ball was thrown in the field. When throwing was finished, participants were asked to do the hefting task once again with all of the balls.

Results

Pre-Practice Phase

Initial ability to throw all 48 balls to maximum distances was tested. The results showed that all participants were poor throwers before practice (see Figure 3). Their mean throwing distances ranged from 6.95 m to 9.06 m, much shorter than the average distance (29 m) that skilled throwers could have achieved (Zhu & Bingham, 2008). A three-way repeated measures analysis of variance (ANOVA; size \times weight \times throwing round) conducted on distances of throws revealed effects of ball size, $F(5, 115) = 49.72, p < .001, \eta^2 = .643$, of ball weight, $F(7, 161) = 39.90, p <$

² To ensure that the groups were equivalent in skill, we performed an ANOVA on the previously obtained hefting and throwing data, adding group as a between-subject factor. The results showed no group difference either in hefting, $F(3, 20) = .17, p > .05$, or in throwing, $F(3, 20) = .37, p > .05$, indicating participants were of equal abilities in each group.

³ A tennis ball was selected for practice for three reasons: first, it was a spherical object that approximately the same configuration of size and weight as the object that was shared by the three subsets; second, according to Edwards Van Muijen, Joris, Kemper, & van Ingen Schenau (1991), practice with a light ball promotes the neural adaptations of muscles to the fast speed, which later on could be carried over in throwing the heavier balls; and third, it had a fibrous and elastic surface, so it provided good graspability, durability, and safety for practice.

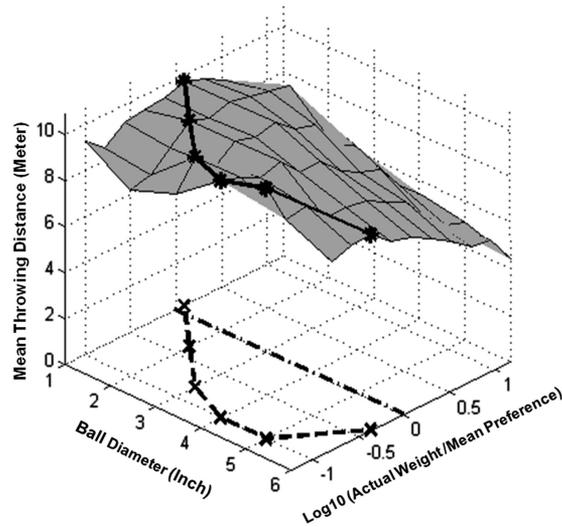


Figure 3. A surface representing mean distances of throws measured before practice as a function of object size and weight selected by hefting. The peak ridge (denoted by stars) of the surface is connected by a line and projected onto the size-weight plane describing the size-weight scaling relation for preferred objects. When the projected line aligns with the 0 value on log-normed weight axis, the preferred weight was thrown to the farthest distance.

.001, $\eta^2 = 0.603$, and of throwing round, $F(2, 46) = 3.82, p < .05$, $\eta^2 = .099$, as well as of the interaction between size and weight, $F(35, 805) = 18.01, p < .001, \eta^2 = .432$. Small balls were thrown farther than larger balls. The mean throwing distance in the first round was farther than the following two rounds, indicating that participants fatigued even though they were allowed to rest between throws. A different weighted ball was thrown to the farthest at each size, suggesting that an optimal weight existed in each size for the maximum distance throwing even when the throwing performance was poor.

Next, we analyzed the hefting judgments. Just as in our previous study (Zhu & Bingham, 2008), we computed the mean of the chosen weights for each size by weighting judgments according to preference: first chosen weight was multiplied by .5, second chosen weight by .33, and the third chosen by .17. Unskilled throwers exhibited a similar pattern of mean judgments as did skilled throwers in previous studies. The mean of chosen weights increased with increasing ball size from $\approx .025$ kg for the smallest objects to $\approx .27$ kg for the largest objects. A repeated measures ANOVA was performed on the chosen weights with ball size as a within-subject factor. The size effect was significant, $F(5, 115) = 40.59, p < .001, \eta^2 = .595$.

In the previous studies, the pattern of mean judgments was representative of the individual participant's choices. The chosen weight reliably increased with ball size. In the current study, we examined the judgments to determine whether the choices were well ordered across ball sizes, that is, whether individual participants selected increasingly heavy balls with increasing size. We computed the succeeding change of each mean chosen weight across sizes by subtracting each participant's mean chosen weight at a given size from that at the next larger size, yielding 120 (5 levels of size difference by 24 subjects) difference scores. We then computed the

percentage of negative changes among the overall changes, which represents the cases where the chosen weight decreased with increasing size. The results showed that choices were not reliably well ordered; 17.5% of the time participants chose a lighter weight lighter in next larger size. The pattern of chosen weights was not as coherent as with the skilled participants in the previous studies (where only 2.5% were lighter for a larger size). Next, we compared choices with throwing performance to see if balls that were thrown to the farthest were chosen in the hefting task.

A surface that reflects the mean distances of throws as a function of both ball size and weight was plotted to reveal the extent to which perception was accurate (see Figure 3). For each ball size and participant, ball weights were divided by the participant's mean chosen weight in the size. This displaced weight levels relative to one another to align the normed weights in respect to choices for different participants and for purposes of computing mean distances for each weight level in terms of the choices. A normed weight of 1 corresponded to the weight selected as optimal. Because weight levels were distributed according to a geometric series, the normed weight levels were log-transformed to achieve approximately equal intervals between levels. Thus, a log-normed weight of 0 corresponded to the weight selected as optimal in each size. Next, the data was placed into bins whose size was selected to yield one data point for each participant in each bin. Then, mean distances for each bin were computed. The mean throw distances formed a surface in a distance \times size \times log-normed weight space.

As can be seen in Figure 3, the surface varied in two respects. First, distances exhibited an inverted-U pattern for each ball size as a function of normed weight. 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 ridgeline representing the mean maximum distance of throws at each ball size. 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 the balls that they could throw the farthest. The projected ridgeline deviated from this axis and gradually shifted to the left as the ball size increased, indicating that participants became worse in selecting balls as ball size increased, and they were overestimating the optimal weights.

Another way to examine whether the affordance was perceived is to compare the mean distances of throws between preferred and non-preferred balls. We calculated the mean distances of throws for the three preferred balls by weighting distances according to the preference: the distance of the first chosen ball was multiplied by .5, the distance of the second chosen ball by .33, and that of third chosen ball by .17. Then, we calculated the mean throwing distances for the four non-preferred balls by averaging distances across the non-chosen balls (with the exclusion of the ball that was thrown to the shortest distance to avoid a possible floor effect caused by the heaviest balls).

As shown in Figure 4, the mean distances decreased as ball size increased, and the distance curve of preferred balls overlapped with that of nonpreferred balls. A repeated-measure ANOVA was performed on the mean distances of throws treating ball size and preference as two within-subject factors. Only an effect for size was significant, $F(5, 115) = 43.97, p < .001, \eta^2 = .614$. These

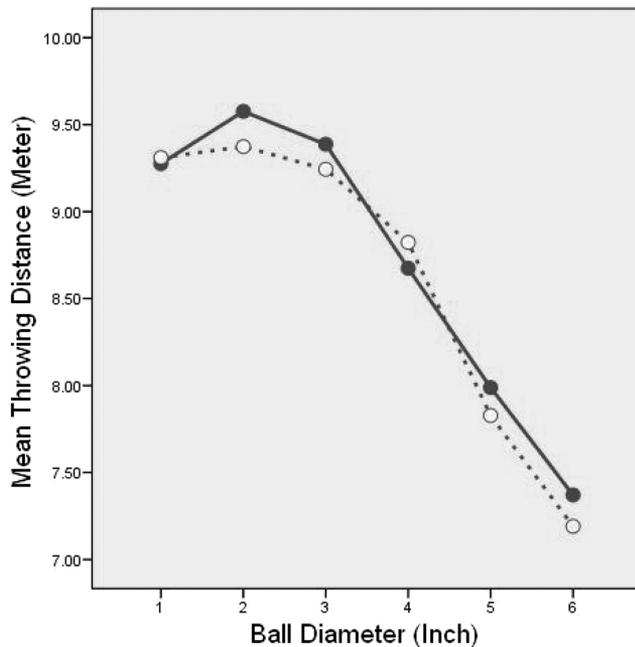


Figure 4. Mean distances of throws as a function of object size and preference. Both the selection of preferred objects and throws were performed by unskilled throwers before practice. Dashed line with open circles represents mean distances of throws of the nonpreferred objects. Solid line with filled circles represents mean distances of throws of the preferred objects.

findings indicated that unskilled throwers did not select the optimal balls that could be thrown to the farthest distance at each size. They were poor in judging the affordance for throwing, and they did not throw preferred balls farther than nonpreferred balls.

Practice Phase

First, we examined changes in throwing performance over the month of practice. We recorded the throwing distance every time each participant threw each ball, yielding sixteen (four times on each of four Mondays) throwing rounds for each subset of balls. Results showed that practice of throwing yielded improved throwing distances for all participants.

As can be seen from Figure 5, maximum distance throws changed in two respects: distances improved and differential performance was achieved with different balls. Distances increased showing improvement of throwing skill with practice. As throwing skill improved, the balls that were optimal for throwing for each group emerged and became increasingly evident. We averaged the four rounds in each week and performed a mixed design ANOVA on the throwing distances including group as a between-subject factor, and practice ball and practice week as the two within-subject factors. The effects of both practice ball, $F(5, 100) = 82.52, p < .001, \eta^2 = .749$, and practice week were significant, $F(3, 60) = 31.28, p < .001, \eta^2 = .505$, but not group, $F(3, 20) = 2.76, p > .05$, suggesting that all groups improved equally in throwing skill over practice weeks and their distances of throws were affected by the practice balls. In addition, there were significant group by practice ball, $F(15,$

$100) = 7.23, p < .001, \eta^2 = .227$, group by practice week, $F(9, 60) = 2.38, p < .05, \eta^2 = .085$, and group by practice ball by practice week interactions, $F(45, 300) = 2.24, p < .001, \eta^2 = .087$, indicating that each group improved the throwing distances differently depending on the practice balls.

We tested the effect of ball for each group at each week. As shown in Table 3, the F ratios for the ball effect increased over practice and achieved significance for all groups by the end of practice. Tukey's post-hoc analyses revealed that each group threw particular balls to the farthest distances each practice week, and eventually, ball 3 was thrown the farthest by participants in the two Constant Density Groups, ball 1 was thrown the farthest in the Constant Weight Group, and ball 4 in the Constant Size Group.

Next, we examined whether the different groups achieved the same levels of skill over the 4 weeks of practice. Study of Figure 5 suggested that some groups might have learned to throw better than others. First, we compared the performance of the three groups that practiced with vision. The average weights of the balls used for practice for the three groups were different as follows: the Constant Weight Group was .069 kg, the Constant Size Group was .112 kg, and the Constant Density Group was .212 kg. Given these differences in the overall average weight thrown by each group, differences in distances of throws achieved by each group might simply be a reflection of these different average weight levels. Thus, we picked the ball of common weight thrown by all three groups, and examined the distances to which it was thrown during all testing sessions to better evaluate potential differences among the groups. The results showed that the same amount of improvement was achieved in all groups (see Figure 6). A mixed design ANOVA on distances of throws treating group as a between-subject factor and the practice round as a within-subject factor showed only a main effect for practice round, $F(17, 255) = 15.08, p < .001, \eta^2 = .456$.

Two groups of participants threw the same constant density balls but one with vision and one without vision during practice. To examine the effect of vision on learning to throw, we compared their distances of throws. The performance was the same. The presence or absence of vision had no effect on learning. A mixed design ANOVA (group \times practice round) on distances of throws showed only a significant effect of practice round, $F(15, 150) = 3.38, p < .001, \eta^2 = .224$.

Post-Practice Phase

Our results supported the hypothesis that unskilled throwers are unable to perceive the affordance for throwing. We also found that unskilled throwers were able to acquire the skill for maximum distance throwing through intensive practice. The key question that remains is whether the ability to perceive the affordance was acquired after practice, and if it was acquired, whether and how it depended on the practice sets or the vision conditions. To answer these questions, we performed a series of analyses on the hefting and throwing data acquired after practice.

First, we compared distances of throws before and after practice to see whether the practice effect was preserved in the final (post-practice) throwing session where the whole set of balls was used (see Figure 7 after practice). The results showed that participants significantly improved the maximum distance of throws. A size by practice (pre or post) by throwing round repeated measure

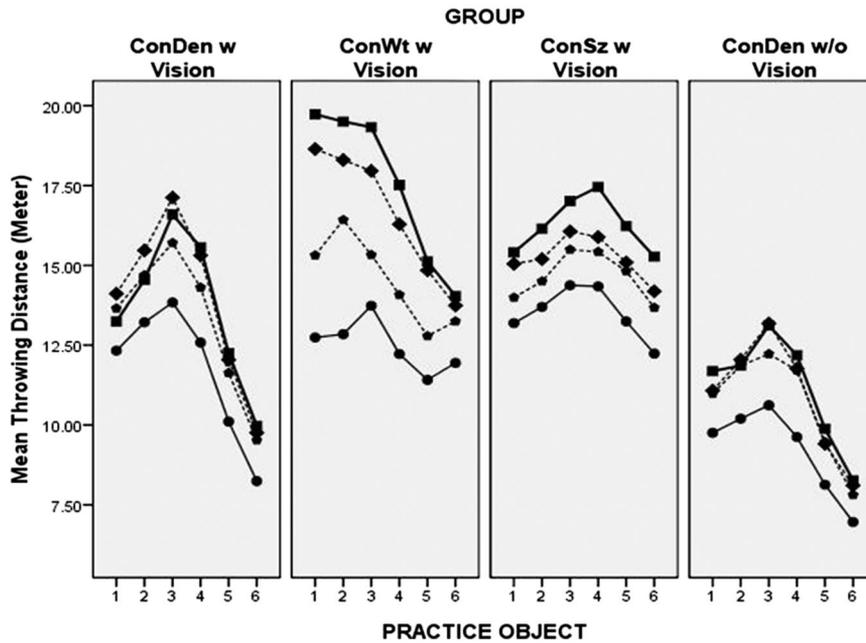


Figure 5. Mean distances of throws during practice as a function of practice object shown in a separate panel for each group. Thin solid lines with filled circles represent mean distances of throws achieved in the first week of practice. Dashed lines with filled pentagons and diamonds represent mean distances of throws achieved in the second and third week of practice. Bolded solid lines with filled squares represent mean distances of throws achieved in the fourth week of practice.

ANOVA was performed on distances of throws. Size and practice were significant, $F(5, 115) = 143.01, p < .001, \eta^2 = .838$ and $F(1, 23) = 127.88, p < .001, \eta^2 = .735$, as was their interaction, $F(5, 115) = 60.61, p < .001, \eta^2 = .687$. Distances increased after practice and more so for smaller balls than bigger ones. Throwing round was not significant, suggesting that participants did not fatigue as they had before practice.

Next, we performed analyses to determine whether participants acquired the ability to perceive the affordance after practice, and if so, whether the perceptual ability depended on the balls used for practice or the presence of vision during practice. Because the results of their throwing also change before and after all the practice, we examined participants hefting judgments first to determine whether their judgments changed as a function of practice, that is, did they make different choices before and after having acquired throwing skill. Then, we analyzed distances of throws to see whether the balls selected either before or after skill acquisition were actually thrown to the farthest distance. We compared the

choices before and after practice only to distances of throws performed after practice to control for the changes in throwing.

The mean chosen weights systematically decreased across the different judgment phases, that is, (1) before or (2) after practice or (3) after throwing with vision. This occurred for all groups except the no-vision group, which chose heavier balls after practice but then returned to their original mean choices after throwing. These mean values need not have accurately reflected changes in the participant judgments if different participants changed their judgments in different directions. To address this possibility, we computed changes in judgments between phases. For each size, the mean weight chosen by each participant in the succeeding phase was subtracted from that in the previous phase, and then divided by the previous weight, yielding the percentage of change in judged weight between phases. We then compared this percentage change between groups, and the results showed that all participants changed their judgments across phases. The preferred weights changed by at least 50% in all sizes and groups. We performed a

Table 3
ANOVA for Effect of Ball for Each Group at Each Practice Week

Object effect $F(5, 460)$	ConDen-V	ConWt-V	ConSz-V	ConDen-NV
Practice-WK1	13.39** # 1;2;3	1.94	1.94	5.73** # 1;2;3
Practice-WK2	15.39** # 2;3	5.78** # 2	1.64	8.69** # 2;3
Practice-WK3	17.08** # 3	12.04** # 1	1.35	9.30** # 2;3
Practice-WK4	21.07** # 3	17.78** # 1	2.20* # 4	10.28** # 3

Note. # Object(s) thrown to the farthest as indicated by the post-hoc analysis.
* $p < .05$. ** $p < .001$.

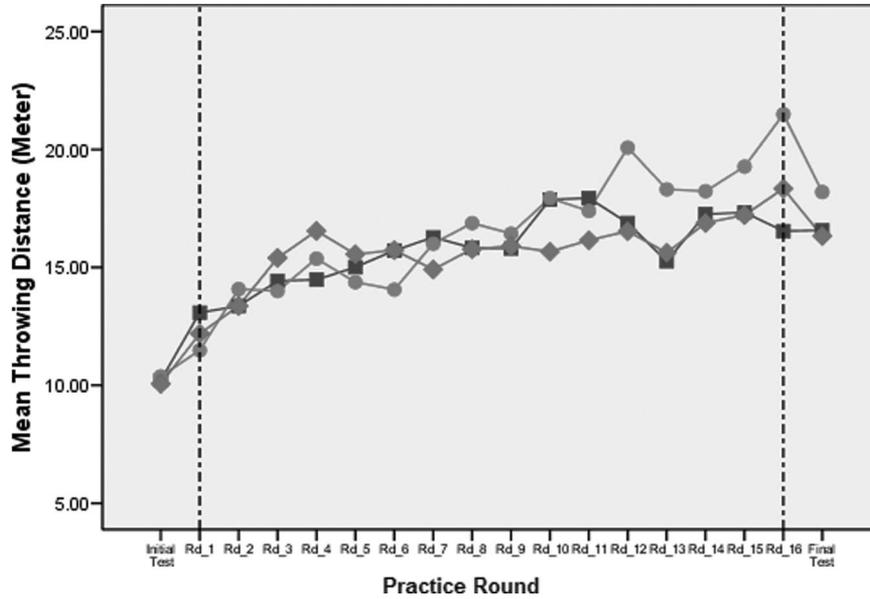


Figure 6. Mean distances of throws of the object of weight common to all groups as a function of throwing round and the group membership in the vision conditions. Squares represent the Constant Density Group; Circles represent the Constant Weight Group; and diamonds represent the Constant Size Group.

three-way ANOVA on the percent changes in preferred weights for the three groups with vision, treating group as a between-subject factor and size and phase difference as within-subject factors. Only a size effect was significant, $F(5, 75) = 2.73, p < .05, \eta^2 = .118$.

The percent change of mean chosen weights was greater for the smaller than larger balls. A separate ANOVA was then performed on the no-vision group treating size and phase difference again as within-subject factors. Only a phase difference effect was found, $F(1, 5) = 7.97, p < .05, \eta^2 = .444$. The no-vision group made greater changes in judgments between the first two phases than between the last two.

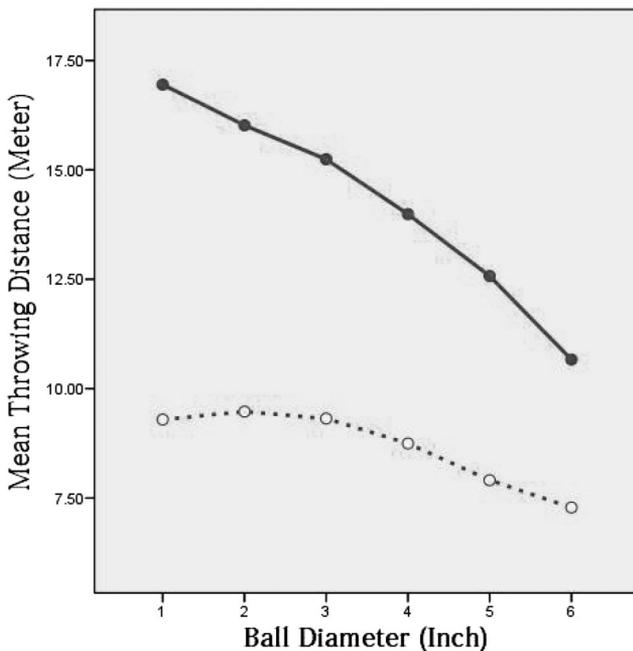


Figure 7. Mean distances of throws achieved before and after practice as a function of object size. The dashed line with open circles represents the distances achieved before practice; the solid line with filled circles represents the distances achieved after practice.

So, the weights being selected in each size were clearly changing, but the next question was whether the choices were becoming better ordered and more accurate. We computed the succeeding change of mean chosen weights as sizes increased (that is, subtracting weight for smaller balls from that for bigger ones) just as we did for the initial hefting session to address the question of ordering, that is, whether participants reliably selected increasingly heavy balls with increasing size. The percentage of negative changes in mean chosen weights was calculated for each group, that is, how often participants selected a lighter weight for the next biggest size. The proportion of negative changes decreased only for vision groups. There was no change in the coherence and orderliness of the judgments for the no-vision group after practice. The no-vision group only improved in this respect after they got to see themselves throwing all of the balls. Vision groups exhibited a higher percentage of negative changes before practice (17.7%) than after practice (7.7%) and after seeing throws (7.7%), indicating that their judgments of weight became more ordered after practice. The no-vision group exhibited a high percentage both before (17%) and after practice (20%), and improved only after seeing their throws (3%).

It is evident that hefting judgments varied across phases in groups with vision to become more reliable. The key questions remained. Did participants become accurate in perceiving the affordance and did the perceptual ability generalize to all balls

including those not experienced during practice? To address these questions, we analyzed the throwing distances as a function of participants' hefting judgments. The throwing distances of the full set of 48 balls achieved after practice were used to examine the accuracy of the hefting judgments made before practice, after practice and after seeing the throws evaluated in terms of predicting the throwability of balls.⁴ We compared the mean throwing distances between the preferred and nonpreferred balls for each set of judgments, and found that the perception of the affordance was only acquired by the vision groups after practice (as well as after seeing the throws), but not by the no-vision group at any phase. As illustrated in Figure 8, the preference curves changed in vision groups after practice and then more so after all the balls had been thrown with vision. However, the no-vision group did not exhibit any difference as a function of preference in any phase. Before practice, the distances for preferred and nonpreferred balls were not different, but for the vision groups, after practice the distances were different. Preferred balls were thrown farther. Two mixed-design ANOVAs were performed on the mean throwing distances to evaluate both the effect of the practice ball sets and the effect of vision during practice. Group was treated as a between-subject factor, and ball, preference and phase as within-subject factors. For the three groups that practiced throwing with vision, each using a different set of balls, effect was significant for ball, $F(5, 75) = 94.61, p < .001, \eta^2 = .823$, for preference, $F(1, 15) = 41.98, p < .001, \eta^2 = .553$, and for phase, $F(2, 30) = 3.60, p < .05, \eta^2 = .124$. As established by the significant phase effect, the distances of throws for the selected balls varied across phases. Since the same throwing data was used, the change of mean throwing distances could only reflect change of judgments. Preference was significant, but of greater interest was a significant two-way interaction between preference and phase, $F(2, 30) = 5.74, p < .01, \eta^2 = .184$. We tested the preference effect at each phase. Results showed that the preference effect did not become significant until participants had acquired the throwing skill, $F(1, 45) = 33.75$ after practice, and $F(1, 45) = 52.17$ after seeing throws, $p < .001$, indicating that participants became sensitive to the optimal balls only after the throwing skill had been acquired, and they became even better after seeing the throws as shown by the increase in the proportion of variability accounted for by the preference effect (partial omega square increased from 0.07 to 0.47 to 0.58). It is important that neither group nor interactions between group and any other factors reached significance, indicating that all groups behaved similarly in choosing the optimal ball for different sizes at different phases.

For two groups that practiced throwing using constant density balls either with or without vision, a significant effect was found for ball, $F(5, 50) = 69.55, p < .001, \eta^2 = .840$, and for preference, $F(1, 10) = 20.30, p < .001, \eta^2 = .480$. However, significant interactions were also found between preference and phase, $F(2, 20) = 3.53, p < .05, \eta^2 = .176$, and most importantly, between group, preference, and phase, $F(2, 20) = 3.91, p < .05, \eta^2 = .192$, indicating that the two groups behaved differently in choosing the optimal balls at different phases. A separate ANOVA was performed to examine the preference effect at each phase and in each group. The vision group demonstrated no preference difference before practice, $F(1, 30) = 2.51, p > .05$, and a significant preference effect after practice, $F(1, 30) = 11.71, p < .001, \eta^2 = .539$, as well as after seeing throws, $F(1, 30) = 24.77, p < .001,$

$\eta^2 = .712$. The no-vision group only demonstrated a trend for a preference effect after seeing throws, $F(1, 30) = 4.14, p = .052, \eta^2 = .293$, indicating that the blindfolded throwers did not begin to acquire the ability to perceive the affordance until visual perception of the throwing was allowed.

To better reveal the difference between the vision and no-vision groups in acquisition of the affordance, we plotted the surfaces representing mean distances of throws as a function of size and log-normed weight for the two groups after practice and after seeing the throws (see Figure 9). Looking at the image of the ridge of the surface projected on the floor of the graphs, one can see that it often fell to the left of the log-normed weight axis (at 0) that represents the preferred balls. It was apparent that both groups tended to overestimate the optimal weight (the preferred weights are heavier than the actual optimal weights) after practice, however, the participants in the vision group were very accurate in judging smaller to medium sized balls, while the no-vision group consistently overestimated the optimal weight in all sizes. When visual perception of throwing was allowed, both groups exhibited better judgment of the optimal balls. However, the vision group corrected their overestimation of the large balls, while the no-vision group was still not that accurate, exhibiting large variation in their judgments.

The results of both hefting judgments and throwing performance after practice indicated that all unskilled throwers acquired the skill for maximum distance throwing, and their judgment of the optimal balls for throwing changed each time it was assessed. However, only throwers who practiced throwing with vision became sensitive to the optimality of balls, and this was independent of the balls that were experienced during practice, that is, they acquired a general ability to judge the affordance. Throwers who practiced throwing without vision did not acquire the sensitivity to the optimal balls.

Discussion

Previous studies (Bingham et al., 1989; Zhu & Bingham, 2008) showed that people with sufficient throwing experience were able to heft and judge the optimal weight of different sized balls for maximum distance throws, exhibiting an accurate perception of this affordance property. The current study assessed the perception of this affordance by unskilled throwers in the context of their learning to throw.

We hypothesized that the perception of the affordance must be learned because the ability to perform long distance throws must be acquired. This hypothesis was supported by the present results. Before practice, unskilled throwers were found to be poor at judging the affordance for throwing. They were on average overestimating the optimal weight and increasingly so as ball size increased. Their hefting judgments were variable and not well ordered with size, that is, they failed to choose increasing weights with increasing size. Both results indicated that the perception of the affordance for maximum distance throwing was poor when the throwing skill was poor. However, after throwing practice and acquisition of better throwing skill, throwers who practiced with vision acquired the ability to perceive the

⁴ Previously, we had tested the hefting judgments made before practice using the throws performed before practice. Part of the problem is that throwing was poor before practice. So now we tested these same judgments using the superior throws after practice to control for the changes in throwing.

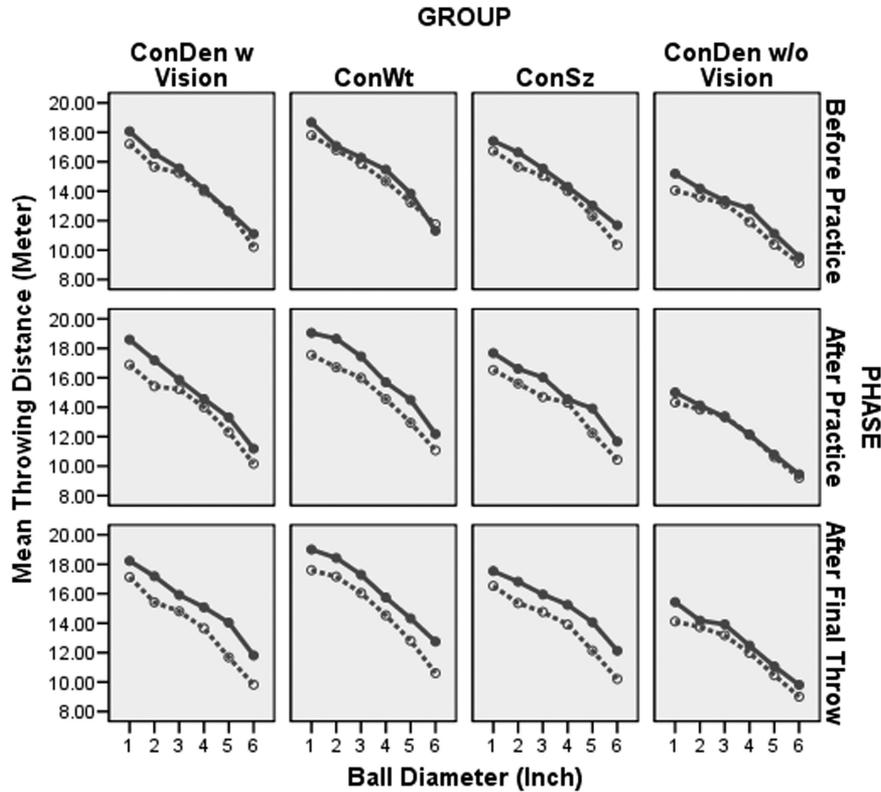


Figure 8. Mean distances of throws achieved after practice (separated for each group) as a function of size and preference across the hefting judgment phases. Filled circles connected with a solid line represent the preferred objects. Unfilled circles connected with a dashed line represent the non-preferred objects.

affordance. They became sensitive to the optimal balls, not only within the subset with which they practiced, but also within the entire set of balls, and their judgments were consistent and well ordered with size, indicating that the acquisition of the skill for long distance throwing enabled participants to well perceive the affordance for throwing. Therefore, learning the affordance for throwing is a perceptual-motor task that entails the coupling of perceptual learning and motor learning.

According to the ecological approach to perception and action (Gibson, 1979/1986), information is required both to detect the useful structure of the environment and to assemble actions used to manipulate the environment. So, the next question we addressed was about how information is acquired through hefting and used for detecting the affordance for throwing. Two hypotheses were contrasted in the current study. The first was the smart perceptual mechanism hypothesis, which is that hefting acts as a smart perceptual device that yields a single detectable information variable that specifies which balls are optimal for throwing. The alternative was the function learning hypothesis, which is that hefting reads both ball size and ball weight and uses them to predict the possible throwing distance based on a function learned in previous experience. Our results rejected the latter and supported the former.

These two hypotheses were tested using the functional relation between distances of throws and ball size and weight, that is, a single valued function (distance) of two variables (size and weight). A surface representing this function can be seen in Fig-

ures 2, 3, or 9. Acquiring the complete function through function learning would require sampling variations in both size and weight, that is, cutting through the surface multiple times. The best sampling would require a series of samples of different weights in a single size followed by another series of different weights in another size, to reveal the way that the optima in the weight dependent curves varied as the size was varied. Sampling along other multiple slices through the space might work equally well, for instance, slices representing different series of constant density objects. This latter sampling might better represent experiences like throwing different sized stones on the beach and then different sized apples in an orchard. Either way, multiple slices through the surface would be required. The important point is that sampling along a single cut through the surface could not be sufficient for learning the entire space via function learning. A single slice provides no data that would allow the function to be extrapolated in any direction except that along the slice itself.

To test this, three sets of balls were constructed and prescribed for practice. Practice with each set of balls represented a single cut through the surface that would be insufficient for learning the complete function via function learning, although interpolation or extrapolation could occur along each cut. If the perception of the affordance requires learning a single valued function of two variables, we would expect that participants who practiced with the constant size set would only learn distance as a function of weight in that size but not in other

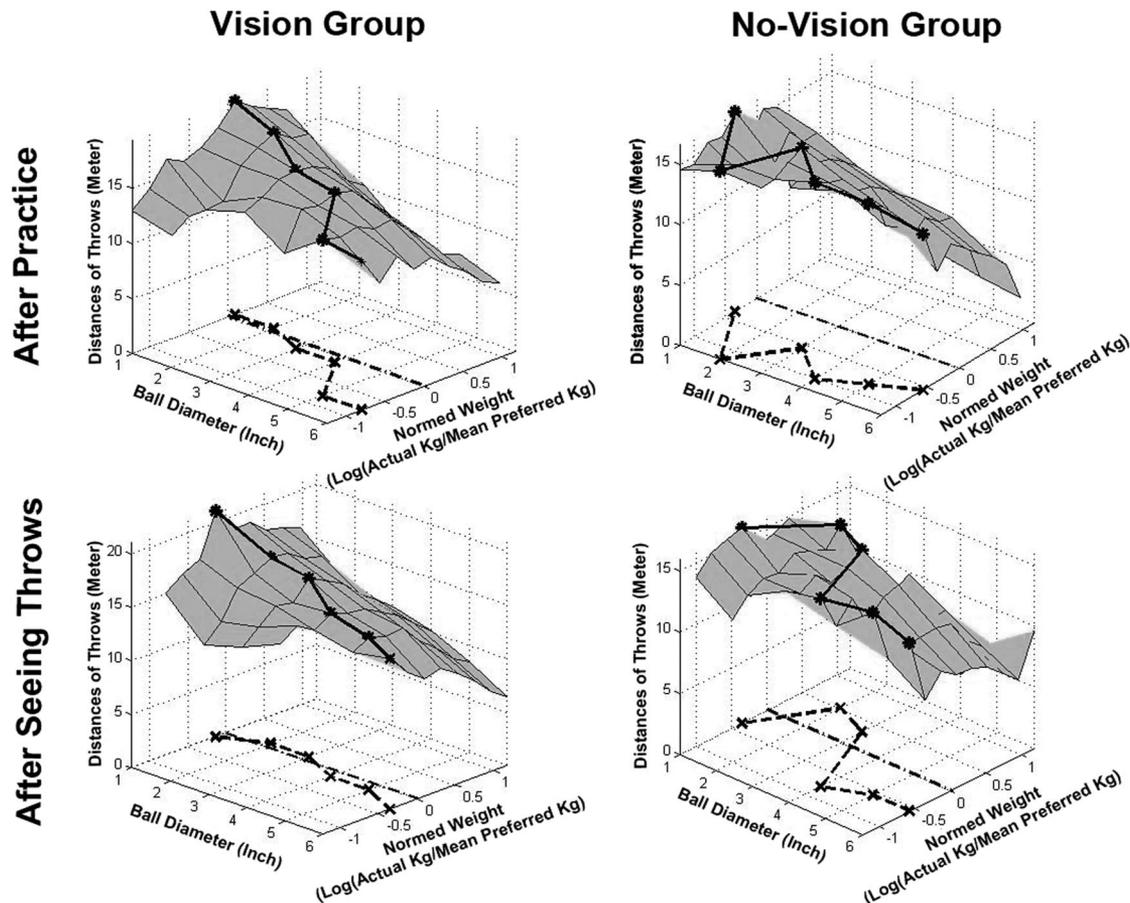


Figure 9. Surfaces representing mean distances of throws measured after practice as a function of object size and weight selected by hefting for the two groups who practiced throwing with vision versus without vision. The peak ridge (denoted by stars) of the surface is connected by a line and projected onto the size-weight plane describing the size-weight scaling relation for preferred objects. When the projected line aligns with the 0 value on the log-normed weight axis, the preferred weight was thrown to the farthest distance.

sizes generally. Participants who practiced with the constant weight set would only learn distance as a function of size but not weight, and those who practiced with the constant density set would only learn distance as a function of the particular covariation of both size and weight that yielded the particular constant density, but not about the variation with different densities or all sizes and weights. Hence, none of conditions would allow learning of the complete function that takes inputs of arbitrary size and weight (within the relevant range). However, the results showed that participants in all three vision groups demonstrated acquisition of the affordance after practice independently of the prescribed set of balls with which they practiced throwing. The perceptual ability generalized to the entire space of balls. Thus, perception of the affordance cannot be a result of function learning that associates perceived weight and perceived size with distances of throws.

According to the smart perceptual mechanism hypothesis, learning the affordance for throwing is to acquire sensitivity to a single information variable made available by hefting with a skilled throwing limb. This requires sufficient variation of the information variable to make it salient together with feedback that reveals the

mapping between the information and distances of throws.⁵ Once the information was acquired, it would generalize immediately to the entire space. Our results showed that all constrained learning conditions yielded a generalized learning of the complete space, suggesting that learning the effect of either size or weight, or both on throwing was sufficient for acquisition of the affordance for throwing. The perceptual system was able to take advantage of the available information to simplify the problem for judging the affordance.

⁵ In principle, it might be possible for participants to learn to appreciate the information by feeling from their throwing movements what objects go the farthest, but as we discussed previously, throwing movements do not predict distances of throws. Neither release angle nor release velocity covaries with object size and weight as do thrown distances. The latter are also a function of the dynamics of projectiles and the effects of object size (and weight) on projectile motion. Thus, the only way to map information from hefting to thrown distances is to be able to see the distances.

However, the acquisition of this sensitivity to the information made available by hefting requires vision to provide knowledge of results about throwing distance. Our results showed that people who practiced throwing without vision did not acquire the affordance after practice, although they did acquire skill for maximum distance throwing, indicating that learning to throw itself did not guarantee the acquisition of the affordance. To learn the affordance, the throwing distances had to be seen as well. This was further supported by the results showing that all groups became more sensitive to the optimal balls when they were allowed to see how far each ball was thrown in the final test.

The result suggests that the perceptual learning involved in acquiring the ability to perceive this affordance is very much like calibration. The perception of metric properties like object distance or object size must be calibrated to allow perceptual guidance of accurate actions like reaching-to-grasp an object (Bingham & Pagano, 1998). Such calibration requires accessory information in addition to the information to be calibrated. For instance, visual (Bingham, 2005) or haptic (Bingham, Coats, & Mon-Williams, 2007; Coats, Bingham, & Mon-Williams, 2008; Mon-Williams & Bingham, 2007) information about the relative location of the hand and a target object at the end of a reach is required to calibrate visual information about object distance or size that can be used then to guide subsequent reaches-to-grasp objects. Presumably, the difference between calibration and perceptual learning is that, in the latter case, the problem is to discover the relevant information variable, whereas in the former case, the problem is to determine the effective scaling relation between the information and the relevant action. So, the accessory information is used in both cases but in different ways.

Our study has shown that the perception of the affordance for throwing was acquired through learning to throw, and it was achieved by a smart perceptual mechanism that mapped information available in hefting to distances of throws. The question remains, however, what was the information made available by the smart perceptual mechanism? An initial hypothesis about the specific nature of the smart mechanism was described and investigated by Bingham et al. (1989), but subsequent research has failed to support that hypothesis. Bingham et al. had suggested that the dynamics of hefting serves as a window on the dynamics of throwing. Thus the effects of ball size and weight should be similar in both hefting and throwing tasks. However, this idea was undermined by the results of Zhu & Bingham (2008) who found that only ball weight, not ball size, affected the release velocity to determine the contribution of the dynamics of throwing to throwing distance. Ball size does not affect throwing.

Zhu, Dapena, and Bingham (2009) tested this hypothesis again. Participants performed maximum distance throws of balls that varied in size and weight. The throwing motions were filmed and digitized. Subsequent analyses yielded the release velocity and release angle in each throw. Statistical analyses were performed on these variables as a function of ball size and weight. The results replicated the previous findings showing that the release velocity was only a function of ball weight. Release angle did not vary systematically with ball size or weight. It only became less variable with increasing throwing skill. Ball size only affected throwing distance through the dynamics of projectile motion by determining the air resistance. Release velocity and angle did not vary with ball size, so ball size had no effect on the dynamics of

throwing. Therefore, the idea that hefting is a smart mechanism because of the symmetry in the dynamics of hefting and throwing must be rejected. Nevertheless, the more general smart mechanism hypothesis was supported by our results in the current study. So, the remaining question is how does this work?

The answer may lie in the finding by Bingham et al. (1989) that the relation between optimal weights and ball size was similar to that of the classic size-weight illusion, in which balls of increasing size must weigh more to be perceived of equal heaviness. If this observation is correct, the optimal balls for throwing in different sizes should all feel of the same heaviness and this would provide the information for the affordance. In this case, perception of the affordance would entail discriminating the perceived heaviness that corresponds to maximum distances of throws. Because the maxima only appear in distances of throws (as a function of both size and weight) and not in the release velocities (which vary only with weight), the only way for perceivers to relate their perceived heaviness to the distances of throws is to see how far balls of each felt heaviness can be thrown. Once the optimal perceived heaviness is identified in this way, the affordance can be perceived, and the perception of the affordance can be generalized to any situation where the optimal perceived heaviness can be detected. Zhu and Bingham (2009) have explicitly investigated whether different sized balls of weights chosen as optimal for long distance throwing are also balls of equal perceived heaviness. They are.

Why optimal objects for long distance throwing are perceived to have equal heaviness remains to be determined. A number of different accounts of the size-weight illusion have been proposed. It is called an "illusion" because perceived heaviness is described as a misperception of weight. Nevertheless, hypotheses to account for the effect suggest functional or adaptive bases for it. One common account is in terms of expectations of experienced heaviness when an object is lifted. The idea is that in experience, larger objects weigh more on average and so one develops an expectation that larger objects should be heavier, and this expectation is used to plan actions that involve the lifting of objects. Objects of equal weight but different size violate this expectation with the result that the larger object is lifted with inappropriately larger force and the experience of the resulting lift yields the perceptual illusion. However, Mon-Williams & Murray (2000) have shown that the illusion persists after an object has been lifted and its weight has been thoroughly tested. The resulting lifting actions are well tuned to the actual weight of the objects. Nevertheless, two objects of equal weight but different size will be perceived to be of different heaviness. Another more recent hypothesis, proposed by Amazeen & Turvey (1996), is that perceived heaviness is a function of an object's rotational inertia rather than simply its mass. This hypothesis is that when smaller objects are held in the hand, the center of mass sits at greater distance from the axis of rotation in the wrist than when larger objects of equal weight are held in the hand. The greater distance yields a larger moment of inertia that resists the rotational movement around the wrist joint. As a result, the smaller object is perceived to be heavier. This hypothesis remains to be confirmed in the case of judging the affordance for long distance throwing. The bottom line is that perceived heaviness is a function of both size and weight and that function covaries with the affordance for long distance throwing.

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