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Learning to throw to maximum distances: Do changes in release angle and speed reflect affordances for throwing?

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ABSTRACT

Bingham, Schmidt, and Rosenblum (Bingham, G. P., Schmidt, R. C., & Rosenblum, L. D. (1989). Hefting for a maximum distance throw: A smart perceptual mechanism. *Journal of Experimental Psychology: Human Perception and Performance*, 15, 507–528) found that skilled throwers could heft objects and select the weight in each size that they could throw to a maximum distance. Bingham et al. hypothesized that this affordance affects hefting and throwing in the same way so that hefting provides a window on throwing. Zhu and Bingham (Zhu, Q., & Bingham, G. P. (submitted for publication). Learning to perceive the affordance for long distance throwing: Smart mechanism or function learning? *Journal of Experimental Psychology: Human Perception and Performance*) found that unskilled throwers could not perceive this affordance, but they acquired the ability to perceive it as they acquired skill at throwing. The affordance property consists of a relation between object size and weight. We now investigated whether object size and weight come to affect throwing as it is learned and if so, how? Three groups of unskilled adults practiced throwing for a month, each with a different set of objects: constant size, constant weight, or constant density. Release angle and speed became more consistent as distances of throws improved, but only speeds exhibited mean changes. Object weight affected mean release speeds, following a power law, as found by Cross (Cross, R. (2004). Physics of overarm throwing. *American Journal of Physics*, 72, 305–312). Speeds decreased as weight increased. These findings showed that the

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affordance was not reflected directly in throwing performance and the hypothesis of Bingham et al. (1989) about how the affordance is perceived was not supported. An alternative account is now proposed.

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1. Introduction

Given graspable objects varying in size and weight, adults who are skilled at long distance throwing are able to pick the weight for each object size that they are best able to throw to a maximum distance. This was shown by Bingham, Schmidt, and Rosenblum (1989), who also found that (for objects of sizes from 5 cm to 16 cm in diameter) the optimal weight increased as the object size increased. These results were subsequently replicated by Zhu and Bingham (2008), who tested a larger range of object sizes and weights and a larger set of both male and female participants. Thus, optimal objects for maximum distance throwing exhibit a very particular functional relation between size and weight.

This is an exemplary example of an affordance property (Gibson, 1979/1986). It is physical, real, and relational. It is composed of a specific relation between the size and weight of graspable objects. It is functional. It is defined in relation to a human action, throwing, and nothing picks out the property but the relevant functional context. In particular, there is no word for this affordance property, at least, not in English. Finally, this complex property is perceptible by hefting graspable objects.

People have to learn to be able to perform effective long distance throws. Accordingly, Zhu and Bingham (submitted for publication) investigated whether people without good throwing skills would be able to perceive the affordance for throwing and, if not, whether they would acquire the ability to do so as they learned to perform effective long distance throws. Zhu and Bingham found that unskilled throwers were unable to select optimal objects for throwing with any accuracy, but that once they had learned to throw long distance (provided with vision), they could also now perceive the affordance. They could accurately select objects they could throw to a maximum distance even though they had no previous experience of throwing some of those objects.

The questions we address in the current study were inspired by these results on perception of affordances for long distance throwing and the fact that a different object weight yields the best distance of throws for each graspable object size. The question is how do object size and weight affect changes in throwing as throwing is learned and, relatedly, how do object size and weight affect throwing once the skill has been acquired. The affordance property determines optimal distances of throws. The trajectory of an object is governed by the dynamics of projectile motion (e.g., Parker, 1977). For a given object, the distance of travel through the air is determined by its initial angle and speed, that is, in the context of throwing, by the angle and speed at release from the hand. Thus, these are the two variables that a person must learn to control and to produce consistently and well to throw objects to relatively long distances of ≈ 20 –30 m. More specifically, our questions in this study were twofold. First, how do release angles and speeds change over the course of learning to throw? Is it only a high speed at release that one must learn to produce consistently or is the release angle also a challenge for control? Second, how do object size and weight affect release angles and speeds over the course of learning and in the end? Object weight has been shown to affect the speed of release in throwing (e.g., Cross, 2004; Edwards van Muijen, Jöris, Kemper, & van Ingen Schenau, 1991; van den Tillaar & Ettema, 2004). Its potential effect on release angle is unknown. The effect of object size on either variable is also unknown, although size has been shown to constrain the throwing patterns (Burton, Greer, & Wiese Bjornstal, 1992).

Bingham et al. (1989) considered the dynamics of throwing and suggested accordingly how object size might affect throwing. When an overarm throw is performed, energy is initially developed by moving the more massive trunk of the body (Jöris, Edwards van Muijen, van Ingen Schenau, & Kemper, 1985; Stodden, Langendorfer, Fleisig, & Andrews, 2006a). Then, through sequential motions of pro-

gressively more distal joints of the arm, the energy is transferred eventually to the long tendons that extend from the forearm through the wrist to the fingers as the wrist is cocked (Hirashima, Kadota, Sakurai, & Kudo, 2002; Jöris et al., 1985; Stodden, Langendorfer, Fleisig, & Andrews, 2006b). This occurs approximately 100 ms before the tendon recoils and the object is finally accelerated and released. Those long tendons that accelerate wrist flexion also control the grasp (e.g., Armstrong & Chaffin, 1978). Bingham et al. (1989) measured changes in wrist stiffness as a function of the size of an object in the grasp and found that larger objects yielded a stiffer wrist due to changes incurred in the length of the tendons and muscles by the grasp. Bingham et al. (1989) hypothesized that optimal weights for throwing are selected in each object size to counteract the changes in wrist stiffness so that the timing of wrist movements would be kept optimal. Again, changes in release angles and speeds would be expected to result, but whether they do so is unknown.

Finally, Bingham et al. (1989) hypothesized how the affordance might be perceived. They suggested that object size and weight might affect the dynamics of throwing and the dynamics of hefting in similar ways and that this similarity would allow hefting to provide information about the affordance. They suggested that the effect of object size on wrist stiffness and the concurrent effect of object weight on the timing of wrist motion would be the basis of this symmetry. This hypothesized mechanism is a type of smart perceptual mechanism as proposed by Runeson (1977). “Smartness” refers to particular lawful circumstances of which the perceptual system takes advantage. The smartness in this case is the hypothesized symmetry. Again, the timing changes should be reflected in changes in release angles and/or speeds. Essentially, this hypothesis requires that object size and weight affect the release angle and/or speed of throwing in a way reflecting the effect on distances of throws. That is, the optimality should be evident in these relevant kinematic properties of throwing. If this were to be found not so, then this particular smart mechanism hypothesis would be disconfirmed (although, another smart mechanism that took advantage of and used a different relevant circumstance is possible).

With this in mind, we also investigated whether release angles and/or speeds progressively came to reflect optimal distances of throws (as a function of object size and weight) as participants acquired skill at long distance throwing. Zhu and Bingham (submitted for publication) found that their participants were unable to perceive the affordance before acquiring the skill and were able to do so after acquiring the skill. Did this change reflect corresponding changes in the pattern of release angles and/or speeds?

To investigate the effect of object size on throwing over the course of learning we asked a group of adults who were initially unable to perform effective long distance throws to practice over a month long period with a set of objects that varied in size but not in weight. To investigate the effect of object weight, we asked another group of participants to practice throwing with objects that varied in weight but not in size. Finally, to investigate possible interactions in the effects of size and weight on throwing, we asked a third group of participants to practice with a set of constant density objects for which size and weight co-varied. This last case would also be most representative of what happens in the world, on the beach or in an orchard, where stones or apples that might be thrown respectively would be of constant density. We expected that both release angles and speeds would initially be highly variable and thus, less than optimal. We predicted that this variability would decrease with practice with accompanying improvement in mean values so that mean release angles would approach an optimum of 36° and maximum release speeds should approach 15–20 m/s. The latter are speeds that have been observed in skilled throwers (Cross, 2004; Zhu & Bingham, 2008). In general, maximum release speeds should decrease with increasing object weight according to the power law relation discovered by Cross (2004) and confirmed by Zhu and Bingham (2008). If the power law relation captures a physically governed regularity as argued by Cross (2004), then the expectation would be that the exponent of the power law would be preserved over the course of learning and the coefficient should change with increases in release speed. We investigated this possibility. The final question was whether object size and weight should interact to affect this relation, and in general the pattern of release angles and speeds should reflect optimal distances of throws.

This study was performed both to study the perceptual learning of the affordance while learning to throw (reported in Zhu and Bingham (submitted for publication)) and to study concurrent changes in the kinematics of throwing (reported herein).

2. Method

2.1. Apparatus

Forty-eight spherical objects varying in size and weight were made for throwing. Six object sizes were determined by the diameters of objects: 2.54 cm (1"), 5.08 cm (2"), 7.62 cm (3"), 10.16 cm (4"), 12.7 cm (5"), 15.24 cm (6"). They were all graspable and corresponded roughly to a small marble, a golf ball, a baseball, a soft ball, a playground ball, and a water polo ball. Eight weights were generated in each of the six sizes starting with the lightest weight that could be constructed in each size, and they increased according to a geometric progression: $W_{n+1} = W_n \times 1.55$. The matrix of object size and weight was constructed so that three subsets could be found in the configuration: a set of six objects at a constant weight of 69 g (varying therefore only in size); a set of six objects at a constant size of 7.62 cm in diameter (varying therefore only in weight); and a set of six objects at a constant density (0.3 g/cm^3 , varying in both size and weight). However, one object was shared by all three configurations (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 similar balls in the otherwise unavailable 12.7 cm size. To do this, a 12.7 cm diameter spherical steel mold was made, 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 that was then heated to form the desired sphere. For some of the heaviest objects 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 objects were pure Styrofoam, such as the object at 12.7 cm size with a weight of 45 g and the object at 15.24 cm size with a weight of 69 g. All objects were tested to be durable enough to withstand impacts from maximum distance throws. The surface of each object was covered with a wrapping of thin, stretchable adhesive tape to produce good graspability and improved durability. Then each object was painted yellow to create identical appearance and surface texture, as well as to increase the visibility of the ball in videos taped during each throwing session.

To manipulate the weights, most of the objects were filled with a sprung brass wire that was injected into the object 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 object. For the extremely heavy weights, lead shot was projected into the sphere together with the foam insulation to mix with the brass wire 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 object so that the desired weights could be achieved.

To measure the distances of throws accurately, we used a measuring tape (100-m long) at distances shorter than 10 m, and a laser rangefinder (Simons Yardage Master 1000) at distances longer than 10 m.

To acquire the kinematic data such as release angle and release velocity during throw, a 2-D motion analysis technique was adopted, which required a video camera with a high speed shutter and a

Table 1

Configurations for object size and weight.

Diameters (cm)	Object weight (g)							
1"/2.54	3.2	5	7.7	11.9	18.5	28.6	44.4	68.8
2"/5.08	7.7	11.9	<u>18.5</u>	28.7	44.4	68.9	106.8	165.5
3"/7.62	18.5	28.7	44.4	68.9	107	166	257	397.6
4"/10.16	29	45	69.7	108	<u>167.4</u>	259.5	402.2	623.3
5"/12.70	45	69.8	108.1	167.6	259.7	<u>402.6</u>	624	967.2
6"/15.24	69	107	165.8	256.9	398.3	<u>617.3</u>	956.8	1483

Note: **BOLD** figures denotes the constant weight subset.

ITALIC figures denotes the constant size subset.

UNDERScored figures denote the constant density subset.

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gravitational reference system. We used a commercially available Panasonic PV-GS500 MiniDV Camcorder (shutter speed range: 1/60–1/8000 s), and made a reference system that consisted of a pole with a tripod at the bottom, and a meter stick that could stand on the ground both horizontally and vertically. A string was tied to the pole with two highly visible marking balls positioned along its length and a plumb at the bottom.

2.2. Participants

Eighteen Indiana University undergraduates were recruited for the experiment. They passed a screening session to participate in the experiment (see the screening procedure). Participants were required to be capable of throwing objects and to have had little prior experience or skill at overarm 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 both practice and testing sessions of throwing.

2.3. Experimental procedure

2.3.1. Screening procedure

A screening procedure was used to select participants. Potential participants were asked to throw three tennis balls to a maximum distance on an outdoor field using their dominant hand. The mean distance of throws 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 distance of throws (29 m) achieved by normally skilled throwers (hence distance ≤ 16 m, according to [Zhu and Bingham \(2008\)](#)).² Participants who did not meet the criterion were thanked for their interest and asked to withdraw from the experiment. Potential participants were not informed in advance of screening about the details of the subsequent experiment including compensation or the number of hours involved nor did they know how participants were being screened, that is, whether we were looking for short or for long distances of throws.

2.3.2. Pre-test of throwing

Participants were led to a flat outdoor and they were asked to throw each object of the entire set of 48 objects to a maximum distance three times using their dominant hand. The radial distance (the distance between the landing point and the releasing point) of each throw was measured and recorded. Participants were encouraged to do some stretching and warm-up throws before the throwing, and if fatigue was felt during the test, participants were allowed to rest. Participants were blindfolded and handed the objects for throwing. The blindfold was used to prevent participants from obtaining feedback about distances of throws of objects from the full set of 48. This was relevant to the study on learning the affordance. The potential role and effect of vision on throwing was controlled in two ways. First, distance of throws was recorded during each week of practice and evaluated relative to the pre- and post-tests. Vision was available during practice. Second, a fourth group of participants was tested, but they are not included in the current report because this manipulation was not relevant to the goals of the current study. Nevertheless, they practiced with the constant density set without vision during practice. Their performance in respect to mean distances of throws was not different from the group that practiced with the same objects and with vision. The two were directly compared using ANOVA and found not different as reported in [Zhu and Bingham \(submitted for publication\)](#).

2.3.3. Practice of throwing

Participants were scheduled for a month long practice of throwing (see [Table 2](#)). They were randomly divided into three groups. To ensure that the groups were comparable, we performed an ANOVA on throwing data obtained from the pre-test including group as a between-subject factor. The

² Subsequently, we determined that the mean distance of throws of three tennis ball throws from the recruited participants was 13.25 ± 2.99 m.

Table 2
Chart for schedule of experimental sessions.

Initial test	Throwing ability test									10 min
	Hefting test w/all objects									0.5 h
Throwing test w/all objects									1 h	
		Monday	Tuesday	Wednesday	Thursday	Friday	Saturday			
A month practice	Week 1	Test w/subset	Instructional practice	Rest	Instructional practice	Rest	Instructional practice	Rest	Test ≈ 2.5 h (35 min × 4 days)	
	Week 2	Test w/subset	Instructional practice	Rest	Instructional practice	Rest	Instructional practice	Rest		
	Week 3	Test w/subset	Instructional practice	Rest	Instructional practice	Rest	Instructional practice	Rest		
	Week 4	Test w/subset	Instructional practice	Rest	Instructional practice	Rest	Instructional practice	Rest		
Final test	Hefting test w/all objects									Test = 2 h (0.5 h × 2tests + 1 h)
	Throwing test w/all objects									
	Hefting test w/all objects									

results showed no group difference in distances of throws ($F(2, 15) = 0.06, p > .5$), indicating that the groups were of equivalent throwing skill at the beginning of the study. The three subsets of objects (constant size, constant weight, or constant density) were assigned to the three groups respectively to be used during practice. According to van den Tillaar (2004), an effective training program for generating fast throws should incorporate training three times per week for 5 weeks. We used two types of objects for a month long training: a subset of six objects with variation of either size or weight or both, and a tennis ball. A tennis ball was selected for practice for three reasons: first, it was a spherical object that was of the same configuration of size and weight as the object that was shared by the three subsets; second, according to Edwards van Muijen et al. (1991), practice with a light ball promotes neural adaptation of muscles to fast speed, which transfers to throwing of heavier balls; third, the tennis ball had fibrous and elastic surface so it provided good graspability, durability, and safety for practice. Participants threw each object to a maximum distance on a field four times each, and the distance of each throw was measured and recorded. 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 of the subset of objects for each participant was calculated and these means were ranked every week. By the end of practice, the participant whose mean distance of throws increased the most received the award. During this and additional practice sessions each week, a tennis ball was thrown back and forth between a thrower and a throwing expert with the distance between them being increased gradually. Participants were given instructions on 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. Participants threw with vision throughout practice.

2.3.4. Post-test of throwing

A week after the practice sessions, participants were again tested in maximum distance throws using each object in the entire set of 48. They were led to the same outdoor field to throw objects. Unlike the pre-test, participants were allowed to see how far each object was thrown on the field while their maximum distances of throws were measured.

2.4. Kinematic measures of throwing

To acquire release angles and release speeds, we videotaped each maximum distance throw during practice. A digital camcorder with a tripod was set up 9.5 m away from the thrower facing perpendicular to the throwing direction. The shutter speed of the camcorder was set at $1/3000$ s. The zoom was adjusted to show both the gravitational reference system and the thrower on the left side of the screen and the projectile motion to the right side. The position and the zoom of the camcorder were fixed once the video for the reference system was recorded. The recorded video was digitized for each throw using the 2-D tracking procedure embedded in SIMI motion analysis software (Version 6). First, the video clip for the reference system was digitized to yield both horizontal and vertical coordinates; next, a calibration was applied to correct errors so that the reference coordinates became orthogonal to each other; then, video clips for each throw were digitized from the release of the projectile (the instant when object was off the tip of the hand) to either the landing of the object or the frame at which the object went out of view. In this way, the positional coordinates (both horizontal and vertical) for airborne objects at each frame were obtained. We then programmed a projectile motion simulator that read both camera frame rate and the positional coordinates to generate the best fitted release angles and velocities (using an air drag coefficient of 0.45).

The 2-D motion analysis required the projectile to be thrown in a plane perpendicular to the camcorder so that the projectile motion could be tracked in two dimensions (horizontal and vertical). To ensure the quality of 2-D tracking, a measuring tape was attached on the ground to the standing point of the thrower and extended along the throwing direction perpendicular to the direction to the camcorder. Participants then were told to throw objects along the direction of the measuring tape.

Meanwhile, an auditory signal for initiation of the throw was given by an experimenter who stood on the measuring tape at the far end. Due to the availability of both visual and auditory cues, participants were able to direct their throws in the required direction.

3. Results

We first analyzed changes in distances of throws and release angle and speed that might have occurred over the course of learning, and then the relations among these changes. Finally, we analyzed the effects of object size and weight on release angle and speed.

3.1. Changes of thrown distance, release angle and speed with acquisition of throwing skill

3.1.1. Distance of throws

The first question was whether distances of throws increased with practice for each of the different groups. To examine an effect of practice, we computed mean distances of throws for each of the six objects for each group before practice, during each week of practice and after practice, and plotted them against objects (1–6). As shown in Fig. 1, the mean distances of throws yielded different curves for all groups but distances increased with practice for all groups. The increase from the pre-test (without vision) to the end of the first week of practice (with vision) was comparable to the subsequent increase from the first to the second week of practice (both with vision).

A 3-way mixed design ANOVA (Group \times Testing Phase \times Object) was performed on distances of throws. We found significant effects for the testing phase, $F(5, 75) = 52.35$, $p < .001$, and for the object, $F(5, 75) = 77.37$, $p < .001$, but no effect for group ($F(2, 15) = 1.03$, $p > .05$), indicating that all groups increased distances of throws, and that distances of throws were affected by the objects. However,

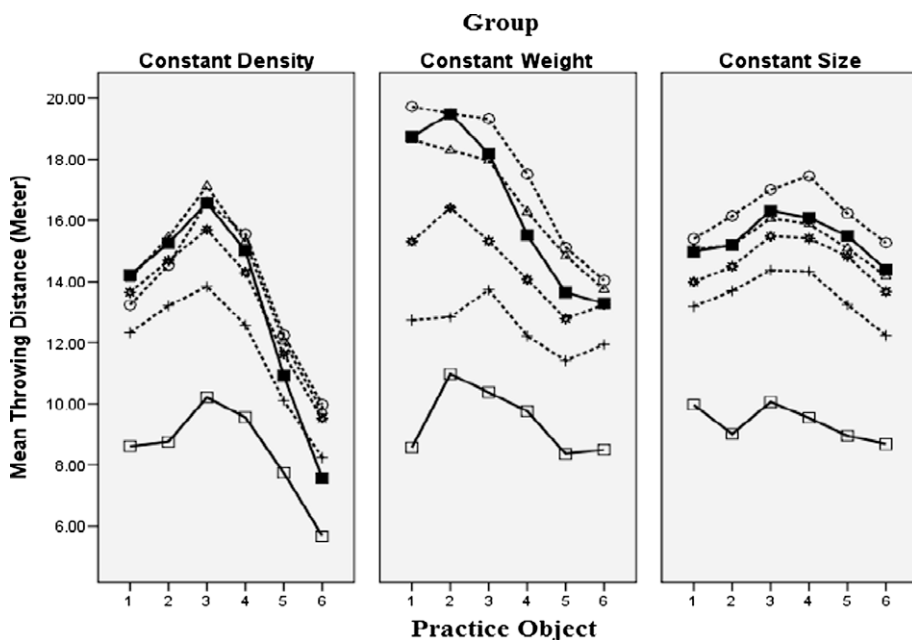


Fig. 1. Mean distances of throws achieved by three groups as a function of object and testing phase. Horizontal axis represents the six objects used for practice by each group: for the constant density group, both object size and weight increased from object 1 to 6; for the constant weight group, object size increased from object 1 to 6 but object weight was constant at 69 g; for the constant size group, object weight increased from object 1 to 6 but object size was constant at a diameter of 7.62 cm. Solid line with open squares: pre-test throws; solid line with filled squares: post-test throws; dash lines represent practice weeks: crosses = week 1; stars = week 2; open triangles = week 3; open circles = week 4.

Table 3

ANOVA Table for object effect on throwing distances.

Object effect ($F_{5,360}$)	ConDen	ConWt	ConSz
Initial throw	9.25** (3;4)	3.92** (2;3)	1.13
Practice WK1	14.09** (3;2;4)	2.42 [†] (3;2;1)	2.68 [†] (3;4)
Practice WK2	13.05** (3;2;4)	6.68** (3;1;2)	2.79 [†] (3;4)
Practice WK3	19.73** (3;2;4)	7.50** (1;2;3)	2.25 [†] (3;4)
Practice WK4	15.24** (3)	12.97** (1;2)	3.71** (4;3)
Final throw	33.35** (3)	15.21** (2;1)	2.17 [†] (3;4)

Note: (1) “[†]” denotes $p < .05$; “**” denotes $p < .01$; (2) numbers in “()” denote the objects that have been thrown to the farthest as shown by Tukey post-hoc analysis ($p < 0.05$).

the 3-way interaction (Group \times Testing Phase \times Object) was also significant, $F(50, 375) = 3.16$, $p < .001$, suggesting that each group behaved differently in their improvement of throwing. Accordingly, we performed separate ANOVAs to reveal how distances of throws were affected by objects in each group and at each testing phase.

As shown in Table 3, the F ratios for the object effect increased across testing phases for all groups. Tukey HSD post-hoc analyses revealed that particular objects were thrown the farthest in each group at each testing phase, and eventually, object 3 was thrown the farthest in the constant density group, objects 1 and 2 (the smallest objects) in the constant weight group, and objects 3 and 4 in the constant size group. With practice, the distances of throws not only increased, but also were increasingly affected by the objects in the practice set, indicating that the physical properties (size and weight) of the objects played an important role in determining the distances of skilled throwing (Newell, 1986).

3.1.2. Release angle

Next, we asked whether and how release angles might have changed over the course of learning to throw long distance. We found that throwing practice did not yield significant mean changes in the release angles. The mean release angles remained unchanged in all groups over practice weeks and for all objects. A 3-way mixed design ANOVA (Group \times Practice Week \times Object) was performed on release angles. None of the effects reached significance. The overall mean release angle (33°) was close to the expected optimum angle of 36° (Linthorne & Everrett, 2006).

However, examination of the variability indicated that release angle did become more consistent with practice and that the variability varied depending on the physical properties of objects. We calculated the standard deviations of release angles for each object and for each participant during the first and last week of practice.

The standard deviations of release angles were high in the first practice week and lower in the last practice week. A 3-way mixed design ANOVA (Group \times Practice Week \times Object) was performed on these standard deviations. The results yielded a significant main effect for practice week, $F(1, 15) = 5.49$, $p < .05$, showing that practice yielded a general reduction of the variability of the release angle. The means (and standard deviations) were for week 1: 7.86° (4.44°), and for week 4: 6.64° (3.00°). There was also a significant main effect for object, $F(5, 75) = 3.88$, $p < .01$, as well as its interaction with group, $F(10, 75) = 2.13$, $p < .05$, showing that the variability of release angles was affected by objects differently in each group. Accordingly, the effect of object was tested using an ANOVA for each group. The results showed a significant effect only in the constant density, $F(5, 90) = 2.27$, $p < .05$, and constant weight, $F(5, 90) = 3.11$, $p < .05$, groups. For constant density, the means (and SDs) for objects 1–6 were 9.04° (3.79°), 7.83° (2.44°), 7.08° (3.56°), 5.52° (2.26°), 4.66° (1.76°), and 5.63° (2.58°), respectively. For constant weight, the means (and SDs) for objects 1–6 were 5.82° (6.28°),

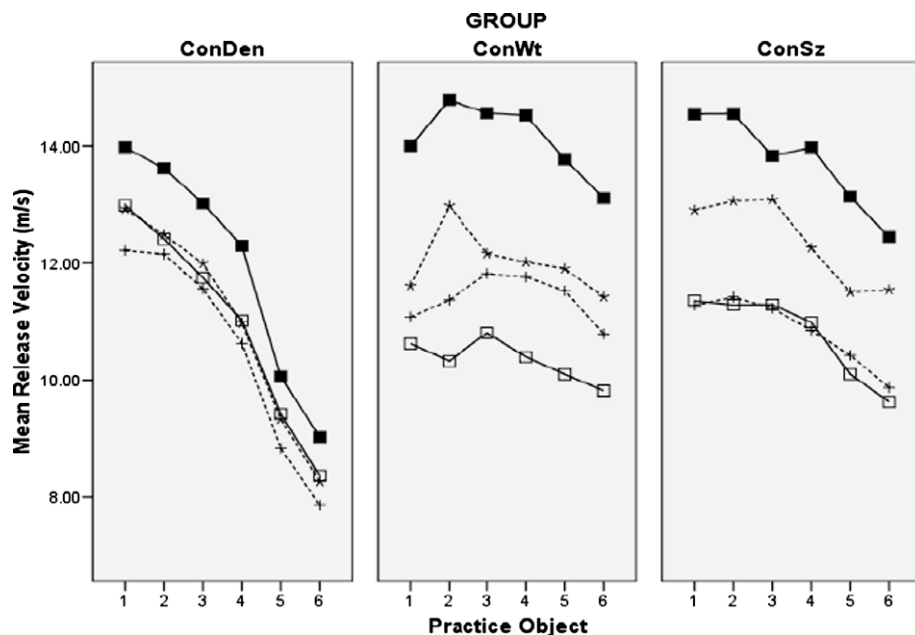


Fig. 2. Mean release velocities achieved by three groups as a function of object and testing phase. Horizontal axis is same as in Fig. 1. Solid line with open squares: first practice week; dotted line with crosses: second practice week; dotted line with stars: third practice week; solid line with filled squares: last practice week.

11.27° (3.59°), 8.13° (3.93°), 7.91° (3.65°), 6.61° (2.86°), and 6.36° (2.87°), respectively. In these two groups, the grasping of increasingly smaller objects yielded greater variability of release angles. The constant size group entailed only variations in object weight and exhibited no object effect. The overall mean for this group was 7.42° ($SD = 3.97^\circ$). However, weight may have interacted with size to amplify the effect of size as indicated by a comparison of the constant density and constant weight groups. Small light objects yielded the greatest variability in release angles.

3.1.3. Release speed

The next question was whether and how release speeds might have changed over the course of learning to throw long distance. As shown in Fig. 2, the mean release speeds increased from early practice to the late practice by as much as 50%, however, each group exhibited different patterns.

A 3-way mixed design ANOVA (Group \times Practice Week \times Object) was performed on release speeds. The results showed significant main effects for practice week, $F(3, 45) = 27.07$, $p < .001$, and object, $F(5, 75) = 88.35$, $p < .001$, as well as for their interaction, $F(15, 225) = 2.20$, $p < .01$. The 2-way interactions between group and object, $F(10, 75) = 21.29$, $p < .001$, and between group and practice week, $F(6, 45) = 2.60$, $p < .05$, were also significant. Therefore, we performed separate ANOVAs to reveal the effect of objects on release speeds in each group and at each practice week.

As shown in Table 4, the F ratios increased over practice week for all groups, indicating that with practice, the release speeds were affected by objects more and more for all groups. Tukey HSD post-hoc analyses revealed that both constant density and constant size groups consistently threw the lighter objects with greater release speeds, and eventually the lightest object was released with the largest speed. However, in the constant weight group, release speed increased equally with practice regardless of the size of the objects,³ implying that release speed varied with object weight but not object size.

³ Although we found a slower speed for the largest object at the end of practice, there were no differences among release speeds of any other sizes.

Table 4

ANOVA Table for object effect on release speeds.

Object effect ($F_{5,300}$)	ConDen	ConWt	ConSz
Practice WK1	38.42** (1;2;3)	1.86	6.78** (1;2;3;4)
Practice WK2	41.99** (1;2)	1.79	4.45** (1;2;3;4)
Practice WK3	44.14** (1)	3.81** (2)	8.03** (1;2;3)
Practice WK4	50.82** (1)	5.64** (1;2;3;4)	8.53** (1)

Note: (1) “*” denotes $p < .01$; (2) numbers in “()” denote the objects thrown with max release speed in order as shown by Tukey post-hoc analysis ($p < .05$).

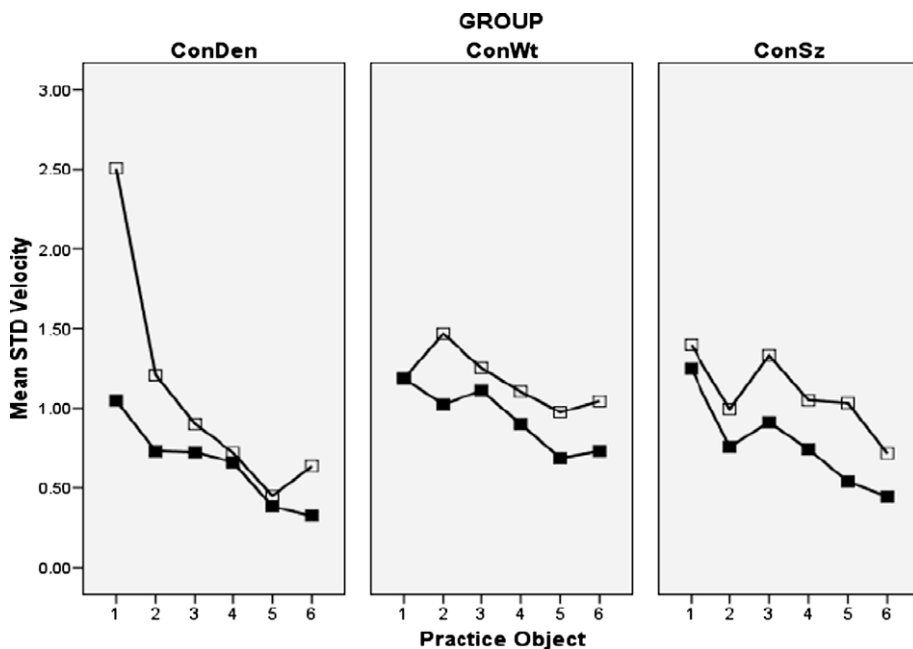


Fig. 3. Standard deviations of release speeds in three groups as a function of objects and practice week. Horizontal axis is same as in Fig. 1. Open squares: first practice week. Filled squares: last practice week.

Next, we evaluated the variability of the release speed by computing the standard deviations for each object and for each participant during the first and last week of practice. As shown in Fig. 3, the variability of the release velocity decreased with practice and with increasing object weight. A 3-way (Group \times Object \times Practice Week) ANOVA conducted on these standard deviations revealed significant main effects for both practice week, $F(1, 15) = 10.05$, $p < .001$, and object, $F(5, 75) = 10.40$, $p < .001$, with no interactions. As revealed by Tukey's post-hoc analyses, the release speed varied less when participants threw larger and/or heavier objects.

3.1.4. Distance of throws vs. release angle and release speed

We found that distances of throws increased with practice. We next explored the relations between these changes and changes in release angle and speed. We performed linear regressions on distances

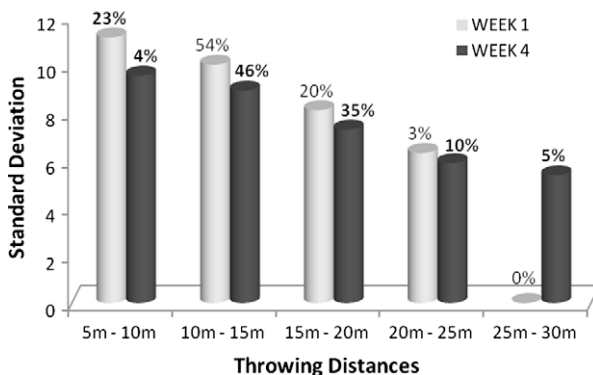


Fig. 4. Standard deviations of release angles as a function of binned distance of throws. Light grey bar: first practice week. Dark grey bar: last practice week. The percentage above each bar represents the proportion of the corresponding release angles in each distance bin.

of throws using either release angles or release speeds to predict distances. Release angle was not significant ($R^2 = 0$, $F(1, 1721) = 0.05$, $p > .05$), indicating that the increase of distance of throws could not be attributed to systematic changes of release angles, although release angles did become less variable and this corresponded to increased distances of throws. The variability of the release angle shrank across practice weeks. At the end of practice, most long distance throws exhibited a release angle close to 33° . We binned the distances of throws by 5 m increments within the range of distances (5–30 m), and calculated the standard deviations of the corresponding release angles in each distance bin during the first and last week of practice.

As shown in Fig. 4, the variability of the release angles decreased as the distance increased in each bin, and comparing the first and last week of practice, the overall variability of the release angle decreased. Furthermore, the proportion of throws in the larger distance bins (that is, 20–25 m and 25–30 m) increased over weeks, indicating that a long distance throw was associated with a less variable release angle and increasingly so with practice.

The release speed was significantly correlated with the distance of throws, $R^2 = .51$, $F(1, 1721) = 1759.62$, $p < .001$. A positive correlation indicated that long distances of throws were associated with high release speeds. To investigate how release speed changed in its relation to the distance of throws with acquisition of throwing skill, we performed separate linear regressions on distances of throws using release speeds at each practice week. As shown in Fig. 5, not only did the R square increase from .40 to .68, but also the slope increased from .91 to 1.39, indicating that distances of throws varied more strongly with release speeds after practice. The tighter relation between release speed and distance was due to the decrease in the variability in release angles and the concurrent increase in release speeds, and thus, thrown distances.

3.2. The effects of object size and weight on throwing

Although we did find that object size affected the reliability with which near optimum release angles were produced, size had no effect on mean angles of release nor did mean angles change with training and practice. Instead, we found that the improvement in throwing performance with training and practice was reflected in an increase of mean release speeds. ANOVA results showed that release speeds also varied as a function of object weight, but not size. Next, we used regression analysis both to confirm this result and to investigate the specific scaling relation between object weight and release speeds. We analyzed the data from the last week of practice because it exhibited the least variability.

First, the analysis confirmed that release speed varied with object weight but not size. We performed a linear regression on release speeds using object sizes in the constant weight group. The regression was not significant ($R^2 = .02$, $F(1, 142) = 2.99$, $p > .05$), showing that size variation did not affect the release speed when object weight was constant. Next, we performed a linear regression

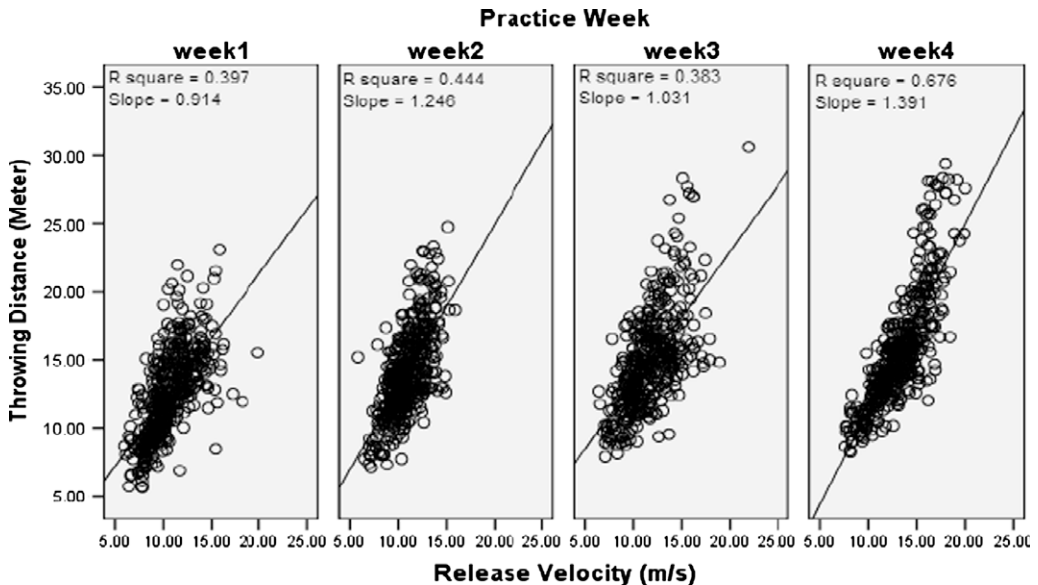


Fig. 5. Regressions of release speeds on distances of throws for each practice week with R squares and slopes of regression lines.

on release speeds using object weights in the constant size group. Because object weight varied as a geometric progression, we log transformed weight. The regression was significant, $R^2 = .12$, $F(1, 142) = 19.02$, $p < .001$, with a significant slope, $\beta_0 = -2.19$, $t = -4.36$, $p < .001$, showing how weight affected release speed when size was constant. If size really does not affect release speed, then the slope of the relation between object weight and release speed should be the same for the constant size and constant density groups. The variation in object sizes for the latter group should not matter. We performed a linear regression on release speeds using log-transformed weights from the constant density group. As shown in Fig. 6, the regression lines in the constant density and constant size groups were parallel as expected. The regression was significant, $R^2 = .45$, $F(1, 142) = 116.12$, $p < .001$, with a significant slope, $\beta_0 = -2.07$, $t = -10.77$, $p < .001$. A multiple regression contrasting the slopes in the two cases revealed no difference between them ($t = -0.25$, $p > .05$). The difference in R^2 in the two simple linear regressions could be attributed to the difference in the range of weights involved respectively. The weight varied from 28.7 g to 256.5 g in the constant size group with a mean weight increase of 45.6 g between objects; the weight varied from 3.2 g to 617.3 g in the constant density group with a mean weight increase of 122.8 g between objects.

Previously, Cross (2004) found that for object weights greater than 50 g, the release speed followed a power function of weight with an exponent of -0.15 . Zhu and Bingham (2008) used simulations of projectile motion to derive release speeds using measured distances of throws and release angles together with object size and weight. The power function between the release speeds and weights greater than 50 g was: $\text{speed} = 14.8 \times (\text{weight})^{-0.15}$. The result replicated that of Cross (2004). (Recall: this was for skilled throwers.) We next investigated whether the same power law was exhibited in the current study and how it might have changed over the course of learning to throw. We selected both constant density and constant size groups (because both entailed variation of object weight), and performed a linear regression on the log transformed release speeds using the log-transformed object weights.⁴ We only used object weights greater than 50 g. First, we tested the final week of practice. The regression was significant, $R^2 = 0.45$, $F(1, 188) = 152.98$, $p < .001$, with a significant slope, $\beta_0 = -0.17$, $t = -12.37$, $p < .001$, and a significant intercept, $\beta_1 = 0.95$, $t = 80.32$, $p < .001$. The power function,

⁴ A log-log linear regression is transformable to a power function.

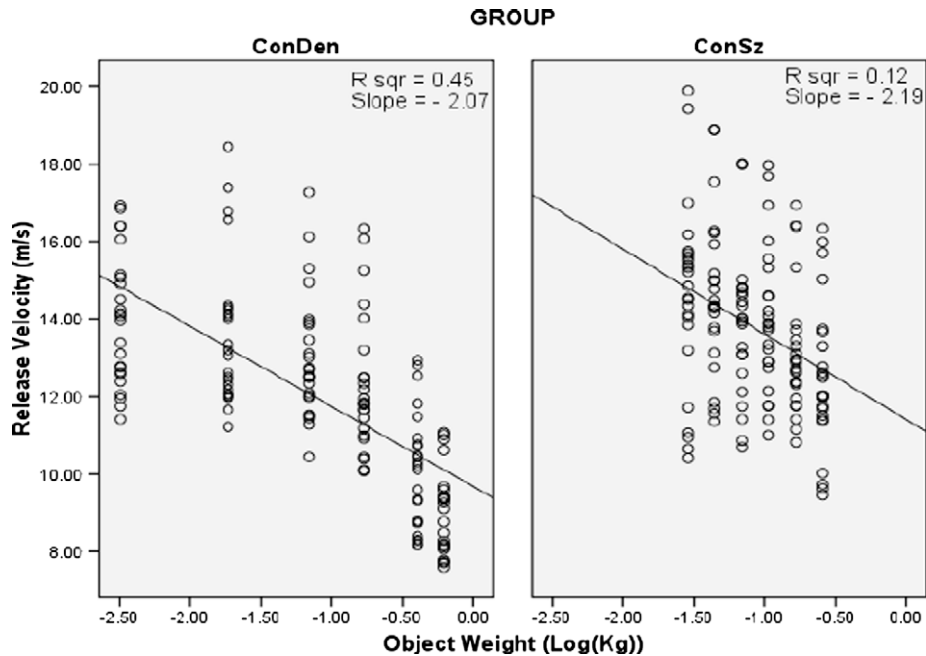


Fig. 6. Regression of log-transformed object weight on release speeds with R squares and slopes for the constant density and constant size groups.

speed = $8.9 \times (\text{weight})^{-0.17}$, yielded a similar exponent (-0.17 vs. -0.15) but a smaller coefficient (8.51 vs. 14.8) of weight than in the previous study of skilled throwers, indicating that the acquisition of throwing skill might only affect the coefficient of weight in the power function. To test this possibility, we performed regressions for each practice week in the current study to see whether the coefficients and/or exponents of weight changed in the power functions. All regressions were significant ($p < .001$). The value of R^2 increased from .33 for the first week to .45 for the last week. The slopes of the regression lines varied from $-.13$ to $-.17$, while the intercepts varied from .88 to .93. (The antilog of .93 is 8.51.) To compare slopes and intercepts between weeks (taken two at a time), we performed multiple regressions (coding the two to-be-contrasted weeks as 1 and -1). The results revealed no differences between slopes ($p > .05$), but a significant increase of intercept from the early practice to the late practice ($t \geq -2.38$, $p < .001$). The exponent in the power function did not vary with practice, but the coefficient corresponding to the intercept did. The increase of the intercept yielded a corresponding increase of release speed by 2.04 m/s. We also performed regressions on release speeds using object weights less than 50 g. The regression was only significant in the first 2 weeks with a very small R^2 value ($R^2 = .07$, $F(1, 94) = 7.06$, $p < .05$ at week one; $R^2 = .05$, $F(1, 94) = 5.62$, $p < .05$ at week two), and the regression failed to reach significance week three and after. This suggested that after a bit of practice at least, the release speed was not affected by object weights below 50 g, and confirmed the previous findings.

4. General discussion

People skilled at performing long distance overarm throws have been found to be able to select the optimal object weight in any specific graspable object size to be thrown to a maximum distance (Bingham et al., 1989; Zhu & Bingham, 2008). Adults who are not yet skilled at throwing were found to be unable to perceive this affordance property (Zhu & Bingham, submitted for publication). They could not correctly select objects that they could throw the farthest, that is, those thrown the farthest either before or after developing throwing skills through training and practice. However, after they had

improved their throwing ability though a month of regular practice, they acquired the ability to perceive which objects were best for throwing. Even though these participants had only trained and practiced with a limited set of objects (for instance, six different weights in a single size), they became able to select the optimal weights in a variety of different sizes with which they had never practiced throwing. When subsequently tested, the selected objects were indeed the objects that were thrown the farthest. The optimal weights were different in each size according to a specific functional relation between size and weight.

The optimal objects were perceived and selected by hefting objects in the hand. Such hefting motions provide information about suitability for throwing. This can be inferred from the fact that experience with a small subset of objects in the course of learning yields an ability to perceive optimality among a general range of throwable objects (Zhu & Bingham, submitted for publication). How does such hefting provide information about throwability? Bingham et al. (1989) hypothesized that a similarity of hefting and throwing motions and dynamics allowed hefting to provide a window on throwing. This hypothesis entailed the assumption that both object size and weight affected throwing motions and dynamics so as to yield maximum distances of throws for objects with the optimal relation between size and weight. Essentially, this assumption is that optimal distances of throws would be reflected in optimal release angles and speeds and that these throwing variables would be affected both by object size and weight. Because people must learn to be able to throw long distance and, at the same time, learn to perceive the affordance of objects for maximum long distance throws, we investigated how release angles and speeds changed over the course of learning and the way that these variables are affected by the sizes and weights of the objects being thrown. The central question was whether we would see an emergent relation between object size and weight, on the one hand, and release angles and speeds, on the other, a relation that reflected the maxima in distances of throws.

As expected, we found that the unskilled throwers exhibited highly variable release angles and speeds and that, with training and extended practice, the variability decreased significantly. However, no changes in mean release angles occurred. Instead, the mean release angle remained constant at 33° near the optimal angle of 36° . Nevertheless, as longer distances of throws were achieved as a result of practice, those throws exhibited low variability in the release angle near the mean of 33° . Mean release speeds exhibited systematic increases over the course of learning and these yielded increased distances of throws when coupled with the reliably optimal release angles. Maximum mean release speeds reached about 15 m/s by the end of the month of practice and the corresponding mean distances of throws were about 20 m. These values were somewhat less than found in previous studies of skilled throwers. However, the majority of participants in the current study were women, whereas those in the previous studies were predominantly men. Thus, the differences in speed and distance are likely attributable to characteristic differences in upper body strength between the genders. Over the course of learning, mean distances of throws nearly doubled. This increase can be safely attributed to acquisition of throwing skill, because the upper body strength of the participants cannot have doubled over the period as a result of the systematic practice.

As expected, the affordance property emerged over the course of learning. Before learning, distances of throws exhibited no optima as a function of object sizes and weights. As learning proceeded, the optima began to appear. Among the constant density set, the third combination of size and weight yielded the longest distances of throws while among the constant weight set, it was the small objects that traveled to the longest distances and among the constant size objects, it was again the third combination of size and weight that yielded the largest distances.

The central question was what effect this emergent affordance would have on release angles and speeds of throws. Neither object size nor weight was found to affect mean release angles. However, object size did affect the variability of release angles. Variability was greater for smaller objects, especially for smaller objects that were also light in weight. Object size did not affect release speeds or the variability of release speeds. However, as expected, object weights affected release speeds strongly. Release speeds decreased systematically as a function of object weights. This functional relation, however, did not reflect the optima in distance of throws. The general conclusion, therefore, was that these measures of throwing performance did not exhibit the pattern of optima in distance of throws in any direct way. Instead, that pattern of distances is produced by the combination of throwing and

projectile motion. In turn, this conclusion means that the Bingham et al. (1989) hypothesis must be rejected. It is not a symmetry of hefting and throwing motions that allows hefting to provide information about how objects affect throwing. The affordance property consists of a functional relation between object size and weight. Our finding was that this property was not reflected directly in the output variables of throwing, that is, release angle and speed.

Zhu and Bingham (2008) performed simulations of projectile motion and found that optima in distances of throws were generated by the dynamics of projectile motion as a function of object sizes and weights combined with a specific pattern of release speeds and a constant angle of release. The pattern of release speeds was that modeled by Cross (2004) who found a power law relation between object weight and release speed. As shown in Fig. 7, we found in the current study that this same power law captured the relation between object weights and speeds of release. Furthermore, we found that the coefficient in the power law increased systematically as a function of learning to throw while the exponent remained unchanged and of the same value, ≈ -0.15 , as that found by Cross (2004) and by Zhu and Bingham (2008) in their respective studies of skilled throwers. The power law applies to throws of objects weighting greater than 50 g. Below this weight, release speeds are only conditioned by the weight of the limb itself and so one sees the same maximum release speed for all such objects.

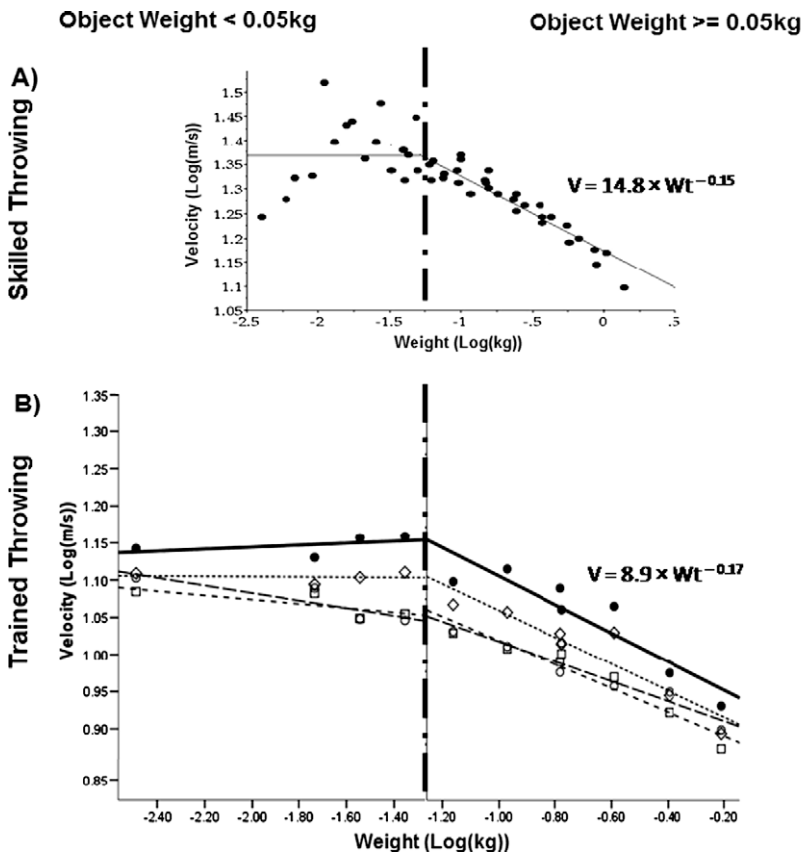


Fig. 7. The functional relationship between log mean release speed and the log object weight for both trained throwing and skilled throwing. Panel A represents skilled throwing, and Panel B represents trained throwing. Each graph shows a vertical line that represents object weight = 0.05 kg. The power functions represent object weights greater than 0.05 kg. In panel B: dashed line with open circles: first practice week; dashed line with open squares: second practice week; dashed line with open diamonds: third practice week; solid line with filled circles: last practice week.

So, learning to throw long distance is a matter of learning to produce an optimal angle of release consistently while maximizing speeds of release given the lawful constraints imposed by the physics of accelerating the given mass. Learning to perceive the affordance that emerges, however, cannot be a matter of sensing similar effects of objects on the motions of throwing and hefting. Instead, Zhu and Bingham (submitted for publication) have suggested that it must be a matter of discovering the perceived heaviness that corresponds to objects that go to the greatest distances. Bingham et al. (1989) showed that the functional relation between size and weight corresponding to optimal objects for throwing happens also to correspond to the well known size-weight illusion function (Cross & Rotkin, 1975; Stevens & Rubin, 1970) for equally perceived heaviness of different sized objects. Objects chosen correctly as optimal for long distance throwing also feel of the same heaviness even though each different sized object is of a different weight: the bigger the object, the larger the weight. Recently, Zhu and Bingham (2009) confirmed that objects of different sizes judged to be of optimal weight for throwing are also perceived to be of equal heaviness.

We make a final observation about the role of object size in throwing. We noted that the extrinsic tendons to the fingers contribute simultaneously to the control grasping and wrist flexion. Because of this, we expected that variations in object size would affect throwing. We found indeed that the optimal release angle for long distance throws was produced less consistently as objects became small. van den Tillaar and Ettema (2004) studied the kinematics of throwing and found an organization different from the sequential order of joint motions found in some previous studies (e.g., Jöris et al., 1985; Feltner & Dapena, 1986). They found that peak velocity of wrist flexion did not occur at ball release and after the peak velocity of shoulder and elbow. To the contrary, peak velocity of wrist flexion occurred before the peaks for elbow and shoulder and before ball release. Most interesting, wrist flexion velocity was near zero at release. This could well be because of the shared tendons between wrist and fingers and the need for accurate use of the fingers to control release (Hore, Watts, Martin, & Miller, 1995) and in particular, release angle. Apparently, as objects become increasingly small, they present a challenge for such control.

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