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RESEARCH ARTICLE

Felt heaviness is used to perceive the affordance for throwing but rotational inertia does not affect either

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Abstract Bingham et al. discovered a perceptible affordance property, composed of a relation between object weight and size, used to select optimal objects for long-distance throwing. Subsequent research confirmed this finding, but disconfirmed a hypothesis formulated by Bingham et al. about the information used to perceive the affordance. Following this, Zhu and Bingham investigated the possibility that optimal objects for throwing are selected as having a particular felt heaviness. The results supported this hypothesis. Perceived heaviness exhibits the size–weight illusion: to be perceived as equally heavy, larger objects must weigh more than smaller ones. Amazeen and Turvey showed that heaviness perception is determined by rotational inertia. We investigated whether rotational inertia would determine both perceived heaviness and throw-ability when spherical objects were held in the hand and wielded about the wrist. We found again that a particular judged heaviness corresponded to judged throw-ability. However, rotational inertia was found to have no effect on either judgment, suggesting that rotational inertia does not determine perceived heaviness of spherical objects held in the hand, as it did for the weighted-rod-type objects used by Amazeen and Turvey.

Keywords Affordance · Throwing · Rotational Inertia

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Introduction

An object of graspable size and liftable weight affords throwing. Bingham et al. (1989) investigated the perception of an affordance for throwing. In their study, spherical objects of different weights in a particular size were given to participants to judge the throw-ability, that is, the optimal weight for the size that could be thrown to a maximum distance. The task was intuitive, and participants exhibited strong preferences in each of four graspable sizes of objects. Participants hefted[1] objects and selected larger weights in larger sizes. A week later, when participants were asked to throw every object (4 sizes × 8 weights = 32 objects) as far as they could, the preferred objects were reliably thrown to the farthest distances

[1] To heft an object, participants held it in the hand and oscillated it around the wrist or oscillated the elbow to cause the hand to bounce at the wrist. See Bingham, et al. (1989) or Zhu and Bingham (2008, 2010) for additional details. Bingham et al. (1989) first piloted the judgment in a free response condition to see what participants would do naturally to perform the judgment task. The experimenters then adopted what they observed these participants to do and regularized it, so all future participants would then perform the same relatively simple but nevertheless representative action.

outdoors on a field. These results were replicated by Zhu and Bingham (2008) using a larger number of object sizes and weights (6 sizes × 8 weights = 48 objects). Therefore, throwers were able to perceive a throwing affordance property that corresponds to a specific relation between object size and weight.

Unsuccessful attempts have been made to discover the information that allows for detection of this throwing affordance. Bingham et al. (1989) hypothesized that hefting provides information about possible distances of throws for objects of given sizes and weights through similarities in the hefting and throwing wrist and elbow motions. This hypothesis necessarily entailed the assumption that both size and weight affect throwing motions to determine the resulting distances of throws. However, Zhu et al. (2009) investigated release velocities and release angles during throws to determine the effects of size and weight on throwing motions, and found that only weight, not size, affected throwing. Size plays its role only in the projectile motion. Hence, information about the throwing affordance must be available through means other than those hypothesized by Bingham et al. (1989).

Given that the ability to throw long distance must be learned, Zhu and Bingham (2010) suspected that sensitivity to information about the affordance might be acquired in the process of learning to throw. The perception and throwing of unskilled throwers were tested before and after participants practiced throwing for a month. It was found that the ability to perceive the affordance for throwing was acquired only after learning to throw. To what information did throwers become sensitive to be able to perceive the affordance for throwing? To answer that question, the learning experience of unskilled throwers was manipulated. For each of three groups of participants, the object sizes and weights that were experienced during practice were limited to one of three sets, each composed of six objects: A set of different weights but constant size, a set of different sizes but constant weight, and a set of different sizes and weights but constant density. If throwers associatively acquired either a look-up table or a function relating size and weight to distance, then practice with objects that limited the sampling should have limited subsequent perceptual ability to the objects experienced (or, with interpolation and extrapolation, to the dimensions of variation experienced). However, the result was that the ability gained through practice generalized to the entire set of objects, that is, beyond the practice sets. This indicated that throwers acquired sensitivity to an information variable that specified the optimal size–weight relation (and the practice sets were sufficient to allow this).

All of these results left an important question: What is the information detected and used to judge the affordance for throwing? Bingham et al. (1989) had noted that the size–weight relation for the throwing affordance resembled that for the size–weight illusion (Charpentier 1891), where larger objects must weigh more to be perceived as equally heavy as smaller objects. Accordingly, it is possible that perceived heaviness was used for detecting the throwing affordance. This hypothesis was recently tested by Zhu and Bingham (2009, 2011) who found that, indeed, all weights selected for throwing were also perceived as equally heavy by the throwers. Thus, throwers may have used a given felt heaviness to select objects that are best for throwing.

A number of theories have been proposed to account for the size–weight illusion and perceived heaviness. Early studies (Davis and Brickett 1977; Ross 1966) suggested that the illusion was a result of error in planning a lift of an object of a given size. This is expectation theory. If a greater force is planned for lifting a larger object with the expectation that it should be weightier, then when the object is in fact lighter than expected, a perception of relative lightness arises based on inferences from the resulting inappropriate motions. Subsequently, Flanagan and Beltzner (2000) found that the illusory perception of relative weight persisted despite frequent handling of the objects that resulted in appropriately controlled motions of the objects in the hand, suggesting that error in planning due to expectation is unlikely to account for the size–weight illusion. Other theories have been proposed. Among them is the inertia theory of Amazeen and Turvey (1996) who demonstrated that perceived heaviness depended only on patterns of an object's resistance to rotation—the object's rotational inertia. These experimenters manipulated object rotational inertia by manipulating the mass distribution along an axis perpendicular to that about which the rotational wielding or hefting movements took place. Participants grasped and manipulated rods with different configurations of attached mass. The perceived heaviness was found to vary as a function of the rotational inertia, and variants of inertia models have shown similar findings (Kingma et al. 2002, 2004; Shockley et al. 2001, 2004).[2] This finding inspired a series of studies on affordances showing that rotational inertia constrains perception of affordance properties such as a racquet's sweet spot (Carello et al. 1999), a stick's utility for performing either a precision or power action (Hove et al. 2006), and other tool

[2] Note that Kingma et al. (2002, 2004) showed perceptual sensitivity to the first moment of inertia (mass × [distance of center of mass from point of rotation]^1), while Amazeen and Turvey (1996) and Shockley et al. (2001, 2004) showed perceptual sensitivity to the second moment of inertia (mass × [distance of center of mass from point of rotation]^2). The salience hypothesis of van de Langenberg et al. (2006) may account for these differing results. However, at issue presently is the fact that both first and second moments of inertia are functions of the mass distribution. Thus, the fact that inertia variables influence perceived heaviness may account for previously observed size–weight influences on heaviness reports.

use (e.g., Michaels et al. 2007; Wagman and Carello 2001; Wagman and Shockley 2011).

Given these demonstrations of the role of rotational inertia in determining felt heaviness and certain object affordances, we hypothesized that rotational inertia might likewise be relevant to perception of the throwing affordance by determining felt heaviness, assuming that indeed felt heaviness is used to perceive optimal objects for throwing long distance. The current studies were designed to test this hypothesis. By manipulating both object masses as well as mass distributions along an axis perpendicular to that in the wrist about which the hefting motion occurred, we varied the rotational inertias experienced by participants independent of the masses (or weights). This manipulation was inspired by the idea that objects of different sizes yield a placement of the mass in the hand at different distances from the axis of rotation in the wrist and thus a difference in rotational inertia. If participants select for a given constant inertia, then they would accordingly select different masses (or weights) for different sizes.[3] That is, if the felt heaviness is used for detection of the throwing affordance and if the felt heaviness is determined by the rotational inertias, then we expected that participants would select objects for throwing that exhibited the same rotational inertia during hefting, despite differences in size, and furthermore, those objects selected as optimal for throwing should also be perceived as equally heavy. To test this, we expanded a design previously used to test the relation between felt heaviness and the perception of the throwing affordance. The previous design included objects of different sizes and weights that were judged first with respect to throw-ability, and then with respect to heaviness. We now added variations in rotational inertia for each object size and weight combination by placing the mass at different positions within the hand-held objects. This put the mass for each given object size and weight at one of three distances from the axis of rotation in the wrist and thus yielded three different rotational inertias for each size–weight combination. The question was whether this would affect the judgments.

Experiment 1

We tested skilled throwers at the University of Wyoming in Laramie.

Method

Participants

Thirty adults were recruited on the campus of the University of Wyoming. They were college students and faculty members who were free of motor and perceptual deficits, but skilled at throwing. To ensure that the recruited participants were competent throwers, a brief throwing ability test was administered to every participant after informed consent had been obtained. Participants were led to a basketball court in a gym and asked to throw a tennis ball 3 times along the longer side-line of the basketball court. Participation was only granted for those who were able to make two out of three throws beyond the length of a basketball court.[4] Those who could not throw were thanked for interest, and then their participation was discontinued. Although the majority of participants were right-handed, there was one participant who was left-handed.

Materials

We made 20 spherical objects. They were either four or six inches in diameter with 5 different masses in each size. Although large objects were heavier in general than small objects, the mass ranges in the two sizes overlapped so that the 3 heaviest small objects were the same mass as the 3 lightest large objects. To create different rotational inertias for each size and mass (or weight), object masses were located either in the center or just under the surface of the sphere. This was achieved by running a PVC pipe through the center of the sphere and affixing a lead mass either at the center or at the end of the pipe. Objects were covered with tape and painted so that they all appeared the same. Objects were placed in a participant's hand with the inserted pipe parallel to the forearm. See Fig. 1.

Three rotational inertias were produced for an object of a given size and weight by locating the mass either near the wrist (mass at pipe end), at the center of the object or far from the wrist (mass at pipe end turned the other way). Thus, with 5 weights in each of 2 sizes and 3 rotational inertias, a total of 30 distinct size–weight–inertia configurations were created. See Table 1 for object specifications.

Procedure

Calculating the rotational inertias of hefted objects The calculation of the rotational inertia for flexing/extending about the wrist during hefting of the objects required

[3] This hypothesis was suggested to Zhu and Bingham by Eric Amazeen who was acting as a reviewer of Zhu and Bingham (2010).

[4] A previous study (Zhu and Bingham 2008) showed that normally skilled throwers can throw an object like a tennis ball to an average of 95 feet, equivalent to the length of a basketball court.

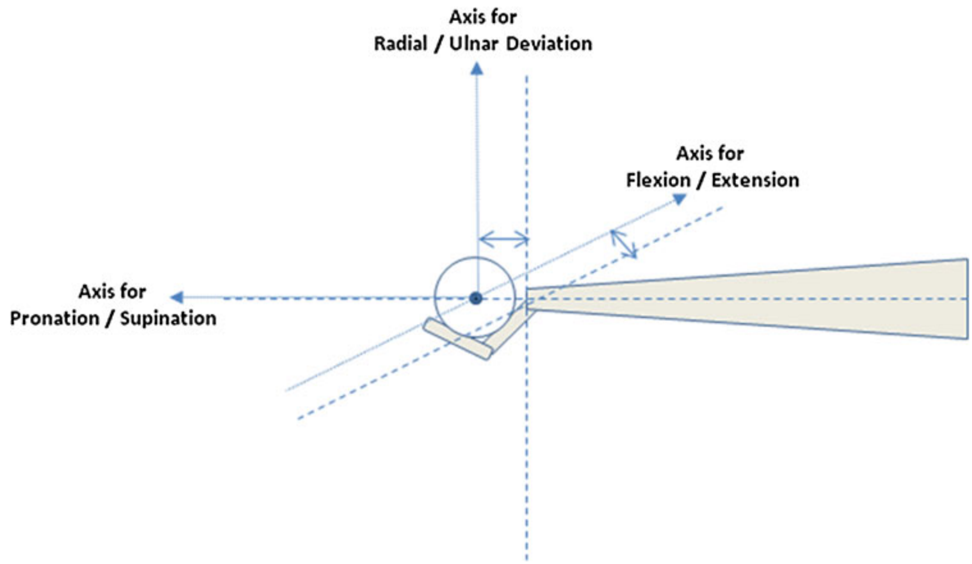

Fig. 1 Illustration of an object held in the hand with all rotational axes labeled. The current experimental task required movement only around the axis of flexion/extension, but not around other axes. The distance between the axes in the wrist and the center of the sphere is indicated by the *length of arrows* for each axis of rotation. Note that there is no *arrow* for pronation/supination because the distance is insignificant

knowing the object-to-wrist (and thus, mass-to-wrist) distance, which depended on how the objects were grasped by the participants and on the size of their hand. Accordingly, participants were given two (center weighted) objects to grasp: one of four inch diameter with a weight of 176 g, and the other of six inch diameter with a weight of 188 g. Participants were asked to grasp each object in a way that they would use to throw it a long distance. The object was always placed in the participant's hand with the pipe inside the object parallel to the forearm. Once participants had settled on their grasp of the object, they were told that this grip should be used for all of the objects in the following tests, and the experimenter measured the distance between the tip of the participant's ulna bone at the wrist and the equatorial plane of the spherical object lying perpendicular to the long axis of the forearm (and the pipe internal to the object). These measurements for each of the two objects (large and small) were used in the following equations to calculate the total rotational inertias for each object for each participant:

$$\begin{aligned}
\boldsymbol{I}_{\text{total}} &= \boldsymbol{I}_{\text{added mass}} + \boldsymbol{I}_{\text{pipe}} + \boldsymbol{I}_{\text{sphere}} \\
&= \boldsymbol{M}_{\text{added mass}}\left(\boldsymbol{D} - \boldsymbol{r}_{\text{sphere}} + \boldsymbol{d}_1\right)^2 \\
&+ \left[\frac{1}{4}\boldsymbol{M}_{\text{pipe}}\boldsymbol{r}_{\text{pipe}}^2 + \frac{1}{3}\boldsymbol{M}_{\text{pipe}}\left(2\boldsymbol{r}_{\text{sphere}}\right)^2\right] \\
&- \left[\frac{1}{4}\boldsymbol{M}_{\text{pipe}}\left(\boldsymbol{r}_{\text{pipe}} - \boldsymbol{d}_2\right)^2 + \frac{1}{3}\boldsymbol{M}_{\text{pipe}}\left(2\boldsymbol{r}_{\text{sphere}}\right)^2\right] \\
&+ \left[\frac{2}{5}\boldsymbol{M}_{\text{sphere}}\boldsymbol{r}_{\text{sphere}}^2 - \frac{2}{5}\boldsymbol{M}_{\text{sphere}}\left(\boldsymbol{r}_{\text{sphere}} - \boldsymbol{d}_3\right)^2 + \boldsymbol{M}_{\text{sphere}}\boldsymbol{D}^2\right]
\end{aligned}$$

where $\boldsymbol{D}$ = measured distance, $\boldsymbol{r}$ = radius of pipe or sphere, $\boldsymbol{M}$ = mass of pipe or sphere, $\boldsymbol{d}_1$ = distance between added mass and edge of sphere (≈ 1 cm), $\boldsymbol{d}_2$ = pipe thickness (≈ 0.1 cm), $\boldsymbol{d}_3$ = shell width (≈ 0.1 cm).

Judging the throwing affordance Each participant was blindfolded and asked to rest the wrist of his or her throwing hand on his or her knee with the palm of the hand facing up. Then, the experimenter placed an object in the participant's hand so that the internal pipe was aligned with the length of the participant's forearm. Participants were asked to use the previously measured throwing grip to hold the object firmly in hand (without moving object by fingers), and then heft (lifting up and down) it only about the wrist to determine whether the object was the best to be thrown to the greatest distance.[5] Six series (2 sizes by 3 mass locations or rotational inertias) of 5 objects each (varying in mass or weight) were presented for judgment.[6] For each series, participants were asked to pick the best 3 objects for throwing (in order from 1st to 3rd best). These choices then were recorded and coded by the experimenter for further analysis. Although the 6 series were tested in a random order, the objects were tested in order of increasing mass within each series, and participants were allowed to re-assess the objects within a series as many times as they needed before providing their judgment. Completion of this task by a participant yielded 6 sets of top three choices, one for each size (2) × mass location (3 = near, medium (center), or far from wrist) set. The three choices were the first, second and third choice weight for each set.

Judging equal heaviness The same objects were used for heaviness judgments. For this task, participants were first

[5] The rotation about all major finger knuckles was restricted so that only wrist was involved in hefting motion.

[6] Participants were told nothing about variations in mass locations or rotational inertias, nor, in general, did they have any awareness of these variations as such. They did, of course, know that objects were varying in size and weight.

Table 1 Object specification

Object ID	Diameter (size/m)	Mass (kg)	Mass location	Inertia series	EXP-1 mean inertia (kg m^2 × 10^4)	EXP-2 mean inertia (kg m^2 × 10^4)
1	Small/0.1016	0.084	Near wrist	1	6.5553 ± 1.7374	3.2678 ± 0.9373
2	Small/0.1016	0.126	Near wrist	1	9.2058 ± 2.6861	4.2224 ± 1.3837
3	Small/0.1016	0.18	Near wrist	1	12.6137 ± 3.9059	5.4499 ± 1.9578
4	Small/0.1016	0.268	Near wrist	1	18.1673 ± 5.8939	7.4501 ± 2.8935
5	Small/0.1016	0.416	Near wrist	1	26.247 ± 8.7855	10.3613 ± 4.2547
6	Large/0.1524	0.198	Near wrist	2	19.5852 ± 4.9898	9.704 ± 2.153
7	Large/0.1524	0.288	Near wrist	2	23.8827 ± 6.805	10.7365 ± 2.7453
8	Large/0.1524	0.434	Near wrist	2	29.5197 ± 9.186	12.0925 ± 3.5231
9	Large/0.1524	0.65	Near wrist	2	39.8336 ± 13.5455	14.5703 ± 4.9483
10	Large/0.1524	0.974	Near wrist	2	54.9738 ± 19.9442	18.2103 ± 5.2842
11	Small/0.1016	0.084	Center	3	8.4862 ± 2.0152	4.5781 ± 1.1504
12	Small/0.1016	0.12	Center	3	10.785 ± 2.5617	5.8171 ± 1.4624
13	Small/0.1016	0.176	Center	3	18.8248 ± 4.4745	10.1474 ± 2.5543
14	Small/0.1016	0.274	Center	3	32.8943 ± 7.8218	17.7254 ± 4.4652
15	Small/0.1016	0.42	Center	3	53.855 ± 12.8087	29.0151 ± 7.312
16	Large/0.1524	0.188	Center	4	21.7677 ± 4.8257	11.882 ± 2.2752
17	Large/0.1524	0.278	Center	4	38.0487 ± 8.445	20.7488 ± 3.9817
18	Large/0.1524	0.424	Center	4	64.4601 ± 14.3163	35.1326 ± 6.7499
19	Large/0.1524	0.642	Center	4	103.8963 ± 23.083	56.6098 ± 10.8832
20	Large/0.1524	0.968	Center	4	161.607 ± 35.9114	88.0409 ± 16.9316
21	Small/0.1016	0.084	Far from wrist	5	11.2162 ± 2.2932	6.6874 ± 1.3638
22	Small/0.1016	0.126	Far from wrist	5	22.0236 ± 4.2144	13.6265 ± 2.5562
23	Small/0.1016	0.18	Far from wrist	5	35.9187 ± 6.6846	22.5482 ± 4.0893
24	Small/0.1016	0.268	Far from wrist	5	58.56261 ± 0.7101	37.0873 ± 6.5877
25	Small/0.1016	0.416	Far from wrist	5	91.501 ± 16.5653	58.2367 ± 10.2218
26	Large/0.1524	0.198	Far from wrist	6	43.6538 ± 7.7194	27.5027 ± 3.8396
27	Large/0.1524	0.288	Far from wrist	6	79.8067 ± 13.1465	52.0921 ± 6.6632
28	Large/0.1524	0.434	Far from wrist	6	127.2097 ± 20.2622	84.3341 ± 10.3653
29	Large/0.1524	0.65	Far from wrist	6	213.9767 ± 33.2875	143.3487 ± 17.1422
30	Large/0.1524	0.974	Far from wrist	6	341.3188 ± 52.4036	229.9617 ± 27.0879

given a comparison object to heft. The comparison object was the one that was previously selected by the participant as most optimal for throwing in one of the 6 series (although the participant was not given this information about the comparison object). Since 6 series of objects were judged in the first task (the affordance task), participants were randomly divided into 6 groups of 5 participants each, corresponding to the 6 series of objects (each series of a given size and mass location), so that the comparison object was from a given series for each group. Once the comparison object was specified, participants were asked to select those objects that were felt to be equally heavy as the comparison object (again in order from 1st to 3rd best) from each of the 5 remaining series. These choices were recorded and coded by the experimenter for further analysis. The 5 series were tested in a random order; however, participants were allowed to re-assess the comparison object and the testing objects as many times as they needed within a series before making their three choices for that series.

Results

Rotational inertias during hefting

We noted that participants all used a distal grip to heft the objects, that is, they placed the object away from wrist so that it sat on the four fingers (not in the palm) with the equatorial plane of the sphere perpendicular to the forearm cutting through the proximal interphalangeal joints. Since participants had different hand sizes, the distance between the center of the object and the wrist varied among participants. This resulted in different rotational inertias during hefting of each object across participants. Nonetheless, the range of magnitudes and changes of rotational inertias were very similar to those reported in previous studies involving wielding rods,[7] which makes the current study comparable to those previous ones.

A repeated-measures analysis of variance (ANOVA) was performed on the calculated rotational inertias for all the objects and participants with size (small and large) and mass location (near, medium and far) as repeated-measures factors. Both size and mass location yielded significant effects. In general and as intended by design, greater rotational inertias resulted when larger objects were hefted ($F_{1,29} = 769.11$, $p < 0.001$) and when object mass was located farther from the wrist ($F_{2,58} = 2{,}399.17$, $p < 0.001$). The mean and standard deviations of inertias for each object are listed in Table 1. The rotational inertias increased more as mass location moved away from the wrist in large objects than in small objects, as indicated by the significant interaction between size and mass location ($F_{2,58} = 2{,}293.31$, $p < 0.001$). Post hoc Tukey tests showed that the resulting rotational inertias were significantly different across mass locations within each size ($p < 0.05$).

Throwing and equal heaviness judgments

For both judgments, participants made 3 choices within each given series of objects. These choices were used to compute a weighted mean preferred mass or inertia as follows:[8] the mass or inertia of the first choice object was multiplied by 0.5, those of the second choice object was multiplied by 0.33, and those of the third was multiplied by 0.17, before the results were summed. Each participant had both a mean preferred mass and a mean preferred inertia for each series of objects for each of the two judgments, throwing and heaviness.[9]

[7] In Experiment 1 of Amazeen and Turvey's study (1996), rods with attached masses were used. Based on the mass and dimension of the rod, for an attached mass of 50 g (the middle magnitude), the corresponding magnitudes rotational inertia for the three different mass displacements (20, 40 and 60 cm from the proximal end of the rod) were 53.89, 113.89 and 213.89 in kg $m^2 \times 10^4$, the range of which is 160 kg $m^2 \times 10^4$. For the objects of greatest mass magnitude in the present study, the corresponding magnitudes of rotational inertia for the three mass locations (near, center and far) were 54.97, 161.61 and 341.32 in kg $m^2 \times 10^4$, the range of which is 286.35 kg $m^2 \times 10^4$.

[8] This approach was developed in Bingham et al. (1989) to compensate for the necessarily discrete way that the objects sampled potential variation in weight, a continuous variable. The weighted average allows a better estimate of the actual preferred or optimal weight value.

[9] For judgments of equal heaviness, the mean preferred mass or inertia for the series of objects from which the comparison object was selected was the mass or inertia of the comparison objects themselves, that is, the first choice object from the previous throwing judgment test.

Two separate mixed-design ANOVAs were performed on participants' mean preferred masses and inertias, respectively, each using group as a between-subject factor, and size, mass location and type of selection (throwing vs. heaviness) as the within-subject factors. Not surprisingly, the results were different for mean preferred masses and mean preferred inertias.

In the ANOVA on mean preferred masses, there was only a significant effect of size ($F_{1,24} = 500.48$, $p < 0.001$) with no significant difference between groups ($F_{5,24} = 1.83$, $p > 0.05$), among mass locations ($F_{2,48} = 0.70$, $p > 0.05$) or between types of selection ($F_{1,24} = 0.05$, $p > 0.05$). As shown in Fig. 2, although greater masses were preferred for large objects (as found also in previous studies), the mean preferred masses for throwing and equal heaviness were the same, and they were the same for all mass locations, indicating that participants preferred a particular mass for long-distance throwing, but it only depended on object size and not the mass distribution (that is, rotational inertia) of the object. Moreover, objects reported to be equally heavy to the referent object varied in rotational inertia and size, but not in mass, indicating that rotational inertia did not determine what objects were perceived as equally heavy. The identical pattern of results for optimal throw-ability and heaviness suggests that the two judgments reflect the same object properties.

In the ANOVA on mean rotational inertias, again, there was no difference between groups ($F_{5,24} = 1.47$, $p > 0.05$) and types of selection ($F_{1,24} = 0.18$, $p > 0.05$). This again indicates that judgments of the throwing affordance and of heaviness were the same. However, size ($F_{1,24} = 333.39$, $p < 0.001$), mass location ($F_{2,48} = 367.16$, $p < 0.001$) and size by mass location ($F_{2,48} = 150.29$, $p < 0.001$) were all significant. Post hoc Tukey tests indicated that mean inertias were significantly different across mass locations within each size ($p < 0.05$), and the interaction was attributed to greater changes in mean inertias over changes in mass location in large as compared to small objects. As shown in Fig. 3, while the mean inertias for both throwing and equal heaviness increased as mass was located farther away from the wrist, they increased more in large objects than in small objects. In other words, objects selected for throwing and for equal heaviness exhibited different rotational inertias as object size and mass location changed. Rotational inertias for selected objects increased as object mass moved farther away from the wrist, and more so for larger than smaller objects.

Discussion

The hypothesis from inertia models of heaviness perception (e.g., Amazeen and Turvey 1996; Kingma et al. 2002, 2004; Shockley et al. 2001, 2004; Turvey et al. 1999; and

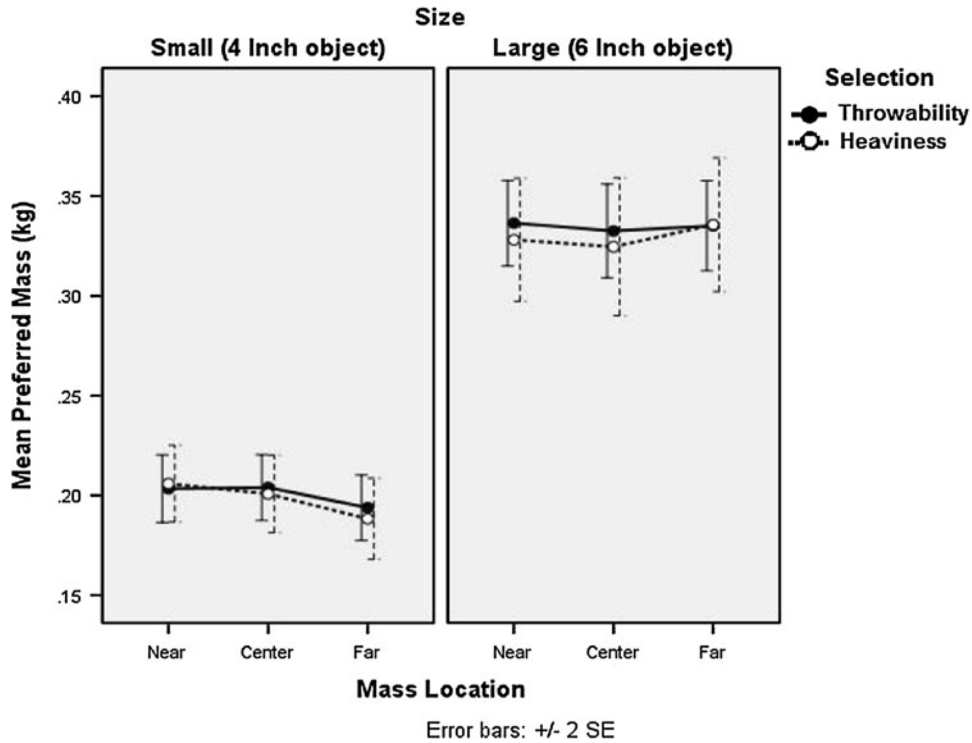

Fig. 2 Mean preferred masses as a function of mass location and object size (the combined data from Wyoming and Ohio are depicted since the results were replicated across locations). The *filled circles* connected by *solid lines* represent the preferred masses for the throwing affordance (throw-ability), and the *open circles* connected by *dashed lines* represent the preferred masses for the equal heaviness to the comparison object

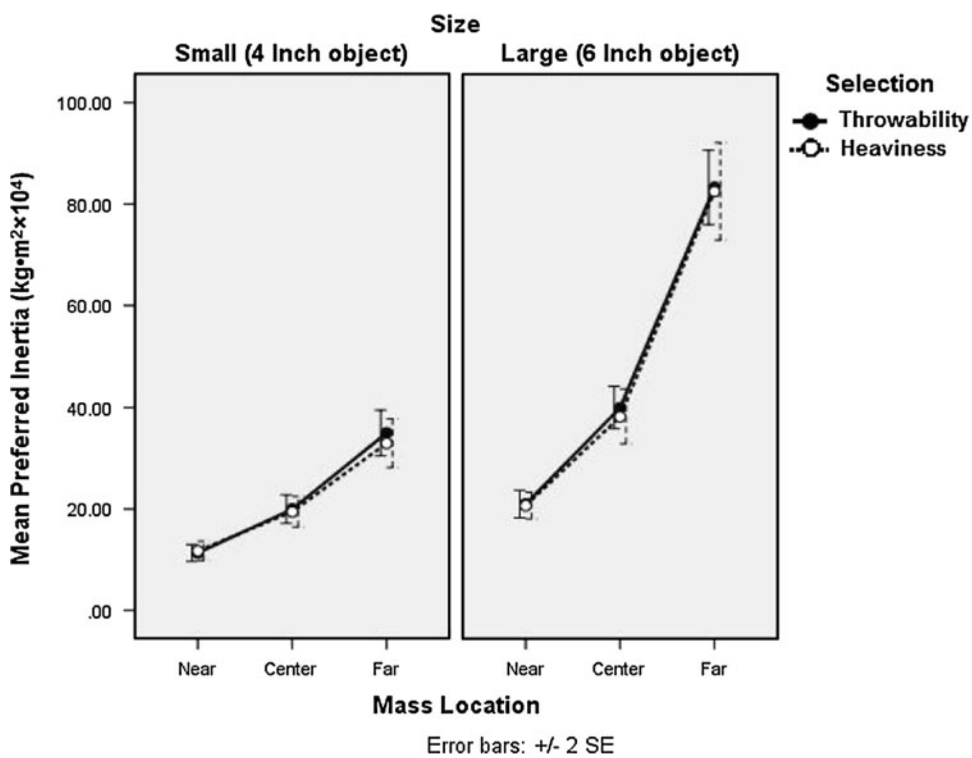

Fig. 3 Mean preferred rotational inertias as a function of mass location and object size (combined data from Wyoming and Ohio). The *filled circles* connected by *solid lines* represent the preferred rotational inertias for the throwing affordance (throw-ability), and the *open circles* connected by *dashed lines* represent the preferred rotational inertias for the equal heaviness to the comparison object

suggested to us explicitly by Amazeen) was that the objects chosen by participants should reflect a preferred rotational inertia. That is, if perception of heaviness and optimal throw-ability are a function of the rotational inertia of the wielded objects, then the mean inertia should be invariant or constant across variations in object size and mass location. Participants should have selected masses (or weights) for the different mass locations and object sizes that result in an invariant rotational inertia. Thus, the inertia theory of heaviness perception predicts that when selected inertias are tested in ANOVA, neither object size nor mass location should be significant. On the other hand, when selected masses are tested, the theory predicts that both object size and mass location should be significant. The results in both cases were inconsistent with these predictions. Finally, we also tested whether judgments of the throwing affordance and judgments of heaviness were the same. We found that they were.

In summary, skilled throwers exhibited the same pattern of choices found in previous studies of the throwing affordance. They preferred greater masses for larger objects. These choices were unaffected by variations in the mass location relative to the moving wrist joint and, thus, by variations in the rotational inertia. This was rather surprising. Finally, these results were the same for judgments of the throwing affordance and judgments of equal heaviness, which, in turn, were not different from one another.

Experiment 2

Because we obtained a result that was inconsistent with other previous results supporting the inertia models of heaviness perception (Amazeen 1997; Shockley et al. 2001, 2004; Turvey et al. 1999; Kingma et al. 2002, 2004), we performed the experiment again at another location and with a different set of experimenters. This time, skilled throwers were tested at the University of Cincinnati, where the experimenters have extensive experience working with the inertia theory. Previous tests of this theory did not involve objects like those in the current studies, that is, with a closed convex hull that could be held in the hand. The previous studies used weighted configurations of hand-held rods that were used to simulate the inertial effects of objects in general (e.g., Amazeen and Turvey 1996).

Method

Participants

Thirteen adult throwers were recruited on the campus of the University of Cincinnati. They were selected using similar criteria described in Experiment 1 in terms of a minimum throwing distance. However, due to difficulty in recruiting participants who could throw a ball the distance of a basketball court (95 feet), women were required to throw the ball 50 feet and men were required to throw the ball 75 feet to qualify for the study.

Materials

The objects described in Experiment 1 were shipped from the University of Wyoming to the University of Cincinnati to be used in Experiment 2.

Procedure

The same experimental procedure was followed to test participants' judgments of the throwing affordance and of equal heaviness, except that participants were not allowed to grasp the objects freely. Instead, the experimenter placed the objects in the center of their palms to be grasped and hefted. This resulted in slight but systematic differences compared with Experiment 1 when the distances of the objects from the center of rotation in the wrist were measured. Also, experimenters measured the displacement of the differently sized objects from the wrist after, rather than before, the experimental trials were completed. This was done to be sure that the measurements could have no effect on perceptual reports.

Results and discussion

Overall, the results replicated those for Experiment 1. As revealed by the repeated-measures ANOVA on participants' mean preferred mass, participants selected the same mass for each object size independent of the mass location ($F_{2,22} = 0.31$, $p > 0.05$). For large objects, a greater mass was selected ($F_{1,11} = 63.42$, $p < 0.001$), exhibiting the same pattern as observed in all previous experiments investigating this judgment task. When the participants' selections were converted into rotational inertias, the mean preferred inertias systematically increased as the location of the mass moved farther away from the wrist. The corresponding ANOVA showed a significant effect for mass location ($F_{2,24} = 62.99$, $p < 0.001$), size ($F_{1,12} = 60.69$, $p < 0.001$), and a size by mass location interaction ($F_{2,24} = 30.26$, $p < 0.001$), suggesting that the selected rotational inertias not only increased as object mass was located farther from wrist, but increased more so for large objects. Just as in Experiment 1, all participants judged the objects selected as optimal for throwing also as equally heavy across both sizes and all three mass locations. There was no significant difference between judgments of throwability and of equal heaviness[10] ($F_{1,12} = 0.32$, $p > 0.05$).

[10] Since previous work (e.g., Shockley et al. 2001) showed that perception of heaviness is also constrained by symmetry of the inertial ellipsoid along with mass, we performed analysis for potential effects of symmetry and found, as expected by design, that it did not play a significant role in determining the judgments.

To compare the data in Experiments 1 and 2, we performed a 4-way (test location (that is, Wyoming vs. Ohio) × size × mass location × type of selection) ANOVA on the mean preferred masses (and then, on mean preferred inertias). For mean preferred mass, only size ($F_{1,41} = 357.55$, $p < 0.001$) and the size × test location interaction ($F_{1,41} = 14.88$, $p < 0.001$) were significant. As revealed by a post hoc analysis, Wyoming and Ohio participants selected a similar mass (about 200 g) for small objects, but Ohio participants selected a somewhat greater mass (about 360 g) than did Wyoming participants (about 320 g) for the larger objects. For data converted to mean preferred inertias, a significant difference was found between the two test locations ($F_{1,41} = 19.45$, $p < 0.001$). Overall, Wyoming participants exhibited greater inertias than did Ohio participants, although the pattern of results otherwise remained unchanged.

Because the calculation of rotational inertias was based on the object-to-wrist distances, the difference in preferred inertias between the two test locations could have been produced by a systematic difference in the object-to-wrist distances. Accordingly, we compared these distances between the two test locations using a mixed-design ANOVA treating test location as a between-subject variable and size as a within-subject variable. The results showed significant effects for both factors but no interaction (location: $F_{1,41} = 51.47$, $p < 0.001$; size: $F_{1,41} = 173.59$, $p < 0.001$). As would be expected, the object-to-wrist distances were greater for large objects in both test locations. However, the object-to-wrist distances from Wyoming were consistently greater than those from Ohio. Wyoming participants were allowed to use their preferred grip when hefting the objects, and they preferred to hold the objects more in the fingers, farther from the wrist. Ohio participants were required to hold the objects centered in the palm closer to the wrist. Notably, these differences did not affect the essential pattern of the results.

General discussion

Previous studies (Bingham et al. 1989; Zhu and Bingham 2008) showed that throwers are able to select the best object for long-distance throwing (that is, the best weight in each given object size). Zhu and Bingham (2010) then found that this perceptual ability is acquired as people learn to throw long distance. They acquire sensitivity to an information variable that specifies the size–weight relation corresponding to the optimal objects for throwing. However, the information used to detect the throwing affordance remained unknown. The current study addressed this remaining issue in two ways.

First, we replicated a previous study (Zhu and Bingham 2011) showing that the objects selected for long-distance throwing are also perceived as equally heavy by throwers. In both studies, an object of a given size that had been previously chosen as the best for throwing was used as the comparison object for participants to judge equal heaviness, and when participants selected objects of different sizes that were felt to be equally heavy to the comparison object, they consistently selected the same objects that they had previously selected as optimal for throwing in each of the different sizes. They did this without any awareness that the two judgments were the same. The result suggests that felt heaviness is used in selecting the best objects for throwing. The felt heaviness must serve as the information for perceiving the throwing affordance.

How do skilled throwers acquire this information, that is, how do they know what heaviness yields the longest distances of throws? Zhu and Bingham (2010, 2011) suggested that the connection must be established when learning to throw by seeing the distances of throws of objects of different felt heaviness. Zhu and Bingham (2010) found that a group of participants who practiced and acquired skilled long-distance throwing without being able to see the distances of throws during practice failed to acquire the ability to perceive the affordance for throwing. They got better at throwing but could not determine which felt heaviness yielded the longest distances of throws. Participants in other groups that were allowed to see distances of throws during practice did acquire the ability to perceive the affordance.

Second, our results were inconsistent with the prediction from the inertia theory, according to which (e.g., Amazeen and Turvey 1996; Shockley et al. 2001, 2004; Turvey et al. 1999; van de Langenberg et al. 2006) rotational inertia should determine felt heaviness. If felt heaviness is used for perceiving optimal throw-ability, then there should be a rotational inertia corresponding to the optimal felt heaviness, and thus the affordance. In our study, participants were allowed to explore different rotational inertias during hefting so that a particular rotational inertia could be selected both as optimal for throwing and as equally heavy. The results clearly demonstrated that participants' selections exhibited different rotational inertias as object size and mass location changed. Participants did not compensate for changes in mass location by selecting different masses to preserve an invariant rotational inertia. Nevertheless, the felt heaviness co-varied with the perceptions of the throwing affordance. We found that the same mass was selected for objects of a given size despite variations in mass location, and the selected mass increased with increasing object size.

The current findings pose a challenge to the generalizability the inertia theory of felt heaviness and the size–weight illusion. According to Amazeen and Turvey (1996), judgments of felt heaviness are a function, not of weight, but of the rotational inertia relative to the joint about which a judged object is moved. They and others (Amazeen 1997; Shockley et al. 2001, 2004; Turvey et al. 1999; van de Langenberg et al. 2006) found evidence supporting this theory, so the question is that why the current results are inconsistent with the theory's predictions. In the previous experiments performed to test the inertia theory, more typical object manipulations of the sort studied directly in the current work were modeled by having participants judge a rigid configuration of weighted rods. Participants grasped one of the rods by its end and then wielded the entire rigid configuration about the wrist joint. The objects to be judged in this way extended well beyond the participant's grasp much as would a tennis racquet or an umbrella. In fact, extensions of the theory have been applied to perceiving affordances like the "sweet spot" in a tennis racquet. In contrast, we have tested the felt heaviness of objects with a closed convex hull[11] (spherical balls) that are fully grasped in the hand and then moved about the wrist. The conclusion must be that rotational inertia does not play the same role with objects of the latter sort as it does with objects of the sort constructed for the previous studies. Apparently, objects with a closed convex hull held enclosed within the hand behave in this regard differently than do objects that extend well beyond the hand and its grasp. The result unfortunately is that the inertia theory cannot provide an account for either the perception of the affordance for long-distance throwing or felt heaviness in the present context.

We have suggested that perceivers use felt heaviness to determine optimal objects for throwing to a maximum distance—that felt heaviness is used as information for perception of the throwing affordance. It is important to clarify what we mean by this. First, information is made available by lawful or invariant relations. In this case, a particular heaviness is invariant with optimal objects for maximum distance throwing. Thus, a given felt heaviness can specify objects that are optimal for throwing. During acquisition of the ability to throw long distance, throwers need only detect the relation between distances of throws and felt heaviness for objects of a given size and, in particular, the felt heaviness that corresponds to the greatest distances. That particular felt heaviness, then, simply specifies the optimal objects for throwing in any size. This is presumably what happened in Zhu and Bingham (2010) where participants practiced throwing with a limited subset of the objects, for instance objects of a single size but different weights. Having done this, they were subsequently able to judge the optimal objects for throwing in sizes not previously thrown. Second, felt heaviness does not in general correspond to distances of throws. Smaller objects are thrown to greater distances than larger objects (even though each is of optimal weight, respectively) because they yield less air resistance. Objects of different sizes that are optimal for throwing will be felt to be of equal heaviness, nevertheless. Furthermore, objects that are not optimal for throwing can also be of the same felt heaviness, just not the particular heaviness that corresponds to the optimal objects for throwing. So, felt heaviness, in general, cannot be identified with the affordance for maximum distance throwing. Finally, the affordance for throwing is a perceptible property of objects, one that can be demonstrated when throwers are capable of throwing the objects to maximum distances. In this context, a particular felt heaviness is information that allows the property to be perceived. It has been suggested that felt heaviness might specify the manipulability of objects in general (Shockley et al. 2004; Turvey et al. 1999), but a broader theory of what felt heaviness means remains to be developed.

Again, we suggest that felt heaviness is used as information about the affordance for throwing. "Information" has been used in a number of different ways in the literature. Some authors have used the term to refer to a (detectable) structured stimulation pattern. Others, and in particular, those working in the dynamic touch domain, have reliably used the term to refer to inertia, which is an object property. Other authors have used "information" to refer to invariants, meaning properties that reliably co-vary with the perceptible item or property of interest. This latter usage actually includes or encompasses both usages above (that is, pattern of stimulation or object property). It is in the sense of invariant that we are using the term.

There is a need for care here. "Heaviness" is itself a term that has been used to refer to a perceptible property of hand-held objects. Previous authors have (mis-)identified "heaviness" with perceived weight and then accordingly referred to the perception as illusory. We and others have pointed out that "heaviness" cannot be about perception of weight as such. It is well known to involve both object weight and size. Here, we are simply noting two things. First, "heaviness" can be experienced with all hand-held objects including those optimal for throwing and those not so optimal. Second, we have shown that a particular "heaviness" corresponds for each individual to optimal objects for throwing, that is, a particular "heaviness" is invariant with objects of a weight in a given size that is best for throwing to the longest distance and, thus, can specify the affordance. This account is very straightforward and well within accepted usage of the term "information."

Finally, once again, it is important to note that perceived optimal throw-ability and heaviness are not the same. They

[11] We adapt this term from geometry.

are not co-extensive. Heaviness is more general. The heaviness of all of the objects in the current studies can be experienced, but obviously not all are optimal for throwing or are perceived as such (see Zhu and Bingham 2011, for additional discussion). One can perceive the best objects for throwing as the ones that are felt of a particular heaviness, and indeed, those are the ones that can be thrown the farthest. The evidence has shown clearly that heaviness can be used as information for optimal throwability.

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