British Journal of Developmental Psychology (2002), 20, 171–183

www.bps.org.uk

Perceiving heaviness by dynamic touch: An investigation of the size–weight illusion in preschoolers

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This study investigates preschoolers' ability to perceive the heaviness of objects by dynamic touch, a perceptual system that relies on the use of the muscle as a sensory organ. In total, 18 preschoolers were asked to hold objects by a handle without being able to see them. The 9 objects differed in mass and volume, allowing us to test the size–weight illusion by dynamic touch. Children were asked in the context of a game to make judgments about the heaviness of the objects. Even the youngest children were sensitive to the rotational inertia of objects, a property that is commonly used by adults to determine the heaviness of an object. Rotational inertia is a function of both volume and mass. This suggests that the size–weight illusion in children is due not to a process of intermodal integration but to children's sensitivity to invariant properties of the input.

The perception of weight is a function of both mass and volume. Specifically, whereas increasing mass will increase perceived heaviness, increasing volume will decrease perceived heaviness by as much as 50% (e.g. Stevens & Rubin, 1970). This well-documented effect is termed the 'size–weight illusion' (Charpentier, 1891; see discussion in Murray, Ellis, Bandomir, & Ross, 1999). In the present experiment, the size–weight illusion will be examined in preschool children.

Size–weight illusion in children

As in adults, the perception of heaviness in children is influenced by both mass and volume. Research has documented a size–weight illusion in children between the ages of 2 and 16 years (Holmberg *et al.*, 1968; Pick & Pick, 1967; Robinson, 1964). The results regarding the developmental trend, however, were contradictory. Robinson

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(1964) tested children aged between 2 and 10 years, and found that the magnitude of the illusion decreased with increased age. Pick and Pick (1967) tested children aged between 4 and 16 years, and found that the magnitude of the illusion increased, decreased, or remained unchanged with increased age, the developmental trend being dependent on the modality through which children could perceive volume. When participants were only able to perceive volume via the modality of touch known as 'haptic touch' (that is, by enclosing the unseen stimulus in their hands), the illusion increased in magnitude from ages 6 to adult. In contrast, when participants were only able to perceive volume visually (the stimulus was lifted with a string), the illusion decreased in magnitude from ages 4 to 6 and then remained unchanged through adults. Finally, when participants could perceive volume with haptic touch and vision simultaneously, the strength of the illusion remained unchanged with age.

A common explanation for the size–weight illusion is based on the assumption that information about mass and volume are perceived independently. Following this assumption, the size–weight illusion would result from a mediating process of mentally integrating information about mass and volume (e.g. Anderson, 1970). If this were true, then the magnitude of the illusion obtained using both visual and haptic information should be the sum of the magnitude obtained using vision only and the magnitude obtained using haptic exploration only. Pick and Pick's (1967) findings did not support this hypothesis. In fact, being exposed to haptic information alone resulted in the largest magnitude of the illusion. Pick and Pick (1967) concluded that intermodal transfer could not account for the results of their study, a conclusion that has been supported by results obtained for adults using a different set of methods (Amazeen, 1999).

An alternative to the model of cognitive integration is a model in which the perception of heaviness is not a function of perceived size but, rather, is a function of a stimulus property that is itself a function of mass and volume. As Gibson (1969) suggested, something that looks like integration of information might be due to the existence of invariant information, relational in nature, that already integrates physical dimensions in the stimulus. Studies in which adult participants hold visually occluded stimuli by a handle have identified rotational inertia as one such stimulus property (Amazeen, 1997, 1999; Amazeen & Turvey, 1996). The present study is an attempt to support this same conclusion with children and thereby extend the conclusions of Pick and Pick (1967) regarding mental integration. In order to make the contribution of rotational inertia apparent, children in this study held visually occluded stimuli by a handle.

Dynamic touch and rotational inertia

The modality of touch that is involved when supporting and making haptic contact with only a part of the object is known as *dynamic touch* (Gibson, 1966)[1]. It is the modality that predominates when adults manipulate objects that are not in view such as tools, utensils, or sporting equipment. Dynamic touch relies on the sensory capabilities of the muscles involved in grasping, lifting, holding, and moving objects. It is distinguished from the haptic mode of touch in which the hands can enclose or run

[1] *This mode of perception was also termed 'kinesthetic perception' (Loomis & Lederman, 1986). However, the term 'dynamic touch' will be used throughout the paper.*

along the outside of the entire object. Research on dynamic touch has been conducted mainly with adult participants. These studies have established that, for adults, dynamic touch is a well-developed modality. It provides access to information about the heaviness, length, width, volume, shape, and orientation of a hand-held object (for a review of the literature on dynamic touch in adults, see Turvey & Carello, 1995).

Dynamic touch is a modality that is sensitive to mechanical stimulation. However, many of the physical dimensions perceived by dynamic touch are dependent on geometric dimensions such as length or volume. The mechanical stimulation that allows the perception of geometric dimensions is the *rotational inertia* of objects. This property is the resistance that an object presents to rotational accelerations; it is the rotational equivalent of mass. Formally, rotational inertia equals the sum of the constituent masses, m, multiplied by the square of the distance, d, from each mass to the point of rotation (rotational inertia = $\Sigma m d^2$). For details on rotational inertia and its calculation, see Goldstein (1980), Kibble (1985), and Symon (1971).

Because rotational inertia is a mechanical dimension, it is a function of mass. However, it is also a function of the mass distribution (i.e. distance of the mass) from the axis of rotation. Hence, stimuli of the same mass but different mass distribution differ in rotational inertia. To show the sensitivity to rotational inertia, different methods have been employed in which rotational inertia was varied without changing other properties of the object such as mass, torque, or centre of mass. One method is to attach metal weights to hand-held rods and to vary mass distribution by varying the position of each weight from the point of rotation. This methodology allows rotational inertia to be manipulated independently from mass, torque, and static moment. Another method is to vary the position of the hand that holds the object. For example, when asked to determine the length of a rod by dynamic touch, the participant's hand could be positioned at one end of the rod or at intermediate locations along the rod. This method makes it possible to manipulate rotational inertia independently of the centre of mass. When participants are asked to hold these stimuli without viewing them and to report their perceptions of heaviness, length, orientation, etc., these perceptual reports are functions of rotational inertia rather than mass, torque, static moment, or centre of mass (Turvey & Carello, 1995).

For children, the modality of dynamic touch has not been investigated as extensively as for adults, although preliminary findings suggest that the principles are similar. Fitzpatrick (1998) investigated the perception of length by dynamic touch in children between the ages of 3 and 5 years. Rods were used that differed in rotational inertia and length (in Experiment 1) or in rotational inertia alone (in Experiment 2). In the first experiment, the participants were asked to hold pairs of occluded rods and to report which of the pair was longer. Children as young as 3 years old responded above chance. Children of all ages consistently reported that the rod with the greater inertia was longer. In a second experiment, children had to adjust the length of a visible rod to match the length of an unseen rod held at one end. Again, perceived length was a function of rotational inertia.

Size–weight illusion by dynamic touch

In addition to the visual and haptic size–weight illusions (Ellis & Lederman, 1993; Pick & Pick, 1967) a size–weight illusion by dynamic touch has been demonstrated in adults (Amazeen, 1997, 1999; Amazeen & Turvey, 1996). Participants were asked to report the heaviness of occluded objects that were held only by a portion of the object (i.e.

volume was neither enclosed in the hands nor visually apparent). The stimuli were either rods with attached weights designed to simulate the changes in rotational inertia that accompany an increase in volume (Amazeen & Turvey, 1996) or cylinders of varying lengths and widths (Amazeen, 1997, 1999). In each case, the size–weight illusion resulted from the dependence of dynamic touch on rotational inertia. These findings were also confirmed with a reanalysis of the size–weight illusion data from Stevens and Rubin (1970) (Amazeen & Turvey, 1996).

Overview

The present study examined the size–weight illusion in children aged between 3 and 5 years. Children rated the perceived heaviness of stimuli that varied in both mass and size. All stimuli were visually occluded and were held by a handle to eliminate any possible visual or haptic information about volume; that is, children judged heaviness solely by dynamic touch. In addition to being the first attempt at demonstrating the size–weight illusion by dynamic touch in children, the present study will extend the results of Fitzpatrick (1998) by evaluating whether children's perceived heaviness is a function of rotational inertia. A demonstration that the size–weight illusion by dynamic touch is a function of particular changes in rotational inertia would further support the conclusions of Pick and Pick (1967) and Amazeen (1999) that the size–weight illusion in children and adults, respectively, does not necessarily result from a cognitive integration of perceived size and weight.

Method

Participants

A total of 18 preschoolers (7 girls and 11 boys) participated in this experiment. They were recruited from a local preschool and tested individually in a room adjacent to their classroom. Their ages ranged from 3 years 1 month to 5 years 4 months ($N = 7$ 3-year-olds, $N = 5$ 4-year-olds and $N = 6$ 5-year-olds).

Materials

A set of nine objects was created. The objects were plastic bottles filled with lead shot and cotton, each attached to a plastic handle. The handle was identical for all objects (height = 0.1 m). To maintain a uniform mass distribution throughout the bottle, the lead shot was evenly distributed and spray-glued on to cotton sheets. The cotton sheets eliminated auditory information about the contents of each bottle. There were three levels of mass (0.125, 0.250, or 0.503 kg) and volume (125, 250, or 500 ml). The three levels of volume resulted from manipulations of both the diameter (0.05, 0.06, or 0.07 m) and height (0.07, 0.1, or 0.15 m, respectively) of the bottle. In order to calculate rotational inertia for rotations about the wrist, the point of rotation in the wrist was taken to be displaced 0.04 m horizontally from the top of the handle, based on measurements from a subset of children[2].

[2] *Although this distance would increase with the age and size of the child (for adults, it is 0.06 m), this would only produce a small, but uniform, change in rotational inertia. It would not change the relative values across stimuli. In the present experiment, we are concerned only with how children order the stimuli, not with overall changes in perceived magnitude across children.*

Because rotations can occur about one of more axes in three-dimensional space, rotational inertia is actually a matrix of nine values. However, when the three axes are chosen to be the symmetry axes of the object in the hand (see Fig. 1), the matrix is reduced to three values I_1, I_2, and I_3, termed the eigenvalues of the rotational inertia matrix. The eigenvalues represent the resistance that the object will present to rotations about each of the three axes in three-dimensional space (indicated by the subscript). In general, for objects that are longer than they are wide, increases in length result in an increase in I_1, whereas increases in width result in an increase in I_3. The dimensions of the objects and the three eigenvalues of the rotational inertia are provided in Table 1.

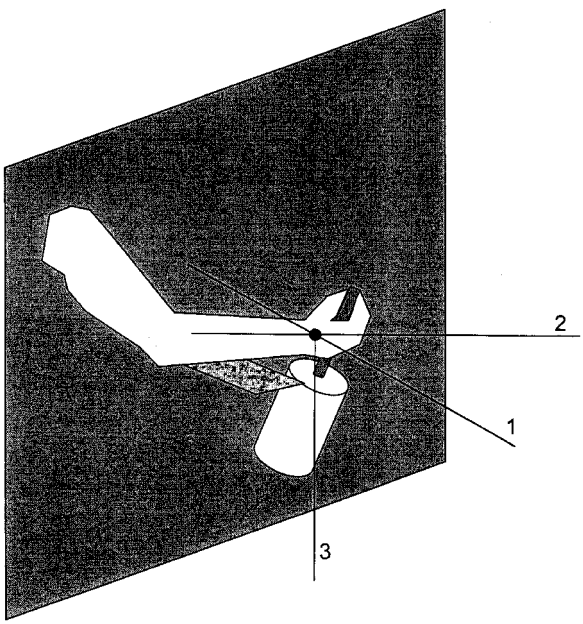

Figure 1. Participant's hand extending through the curtain and resting on the board while holding the stimulus. The three axes are the axes to which the eigenvalues of rotational inertia refer. That is, I_1 is the resistance to rotation about axis 1, I_2 is the resistance to rotation about axis 2, and I_3 is the resistance to rotation about axis 3.

Table 1. Physical dimensions of the stimuli

Number	Mass (g)	Volume (ml)	Log I_1	Log I_2	Log I_3
1	125	500	6.239	6.231	4.927
2	125	250	6.142	6.134	4.778
3	125	125	6.057	6.050	4.645
4	250	500	6.596	6.591	5.243
5	250	250	6.491	6.486	5.077
6	250	125	6.395	6.391	4.925
7	503	500	6.925	6.921	5.551
8	503	250	6.815	6.812	5.376
9	503	125	6.716	6.712	4.215

Note. The eigenvalues of the inertia tensor, I_1, I_2, and I_3 are measured in g $\times$ mm^2.

The participants sat at a small table in front of a computer screen that showed a cartoon mouse at the lower corner on the left side and a small door at the upper corner of the right side. These two items on the screen were connected with a line, presented to children as a hill. The mouse was able to walk to any position on the hill that was pointed to by the cursor. Upon reaching this point, the mouse stopped and waved. The distance walked by the mouse was displayed on the top of the screen (occluded to the participants) and was recorded by the experimenter. The keyboard and cursor were under the control of the experimenter.

A frame holding a curtain was mounted next to the table along the fronto-parallel axis. This curtain obstructed the participant's view to the right side of the table. A wooden board, clamped to the table, extended through the curtain. The participants' right forearm was placed through a slit in the curtain and rested on the board parallel to the curtain (see Fig. 1). Because the forearm was resting on the board, only the joint at the wrist was free to rotate[3].

Procedure

Upon entering the experimental room, the child was seated at the table next to the curtain. All of the stimuli were hidden from view for the entire session. First, the experimenter explained the so-called *mouse game*.

> The mouse lives in a house on the top of a steep hill. When it carries its cheese home, the mouse must rest so that it does not get too exhausted. If the mouse carries a heavy piece of cheese, then it must stop very early on its way up the hill. With a lighter piece of cheese, it can go a bit further before it needs to rest. And with a very light piece of cheese, the mouse can go almost up to its house before it needs to take a rest. The game is about figuring out where the mouse should take a rest.

In three warm-up trials, the child was asked to imagine the mouse carrying a very heavy, a very light, and a medium heavy piece of cheese, respectively. In order to be included in the study, each child had to point at a location on the screen close to the start, the middle, and the end of the hill, respectively. For each warm-up trial, the experimenter showed how the mouse walked up the hill to the spot selected by the child and waved upon arrival. All participants succeeded on these trials.

After completing the three warm-up trials, the child was asked to place their right underarm through the curtain and rest it on the extending board. The curtain occluded the view of the hand and the object without interfering with movement of the wrist. To provide a benchmark for the child, the experimenter placed the medium object (mass = 0.250 kg, volume = 250 ml) in the child's hand and explained that the mouse that carries this cheese has to rest half way up the hill. This step was repeated after every nine trials. A total of 27 trials (three for each object) were conducted in three sessions, each object being presented once per session in a randomized order. In each trial, the experimenter placed the stimulus into the participant's hand and asked the child to hold the object without lifting the forearm from the armrest and to point to the spot on the hill where the mouse would rest first. In most trials, children pointed to the

[3] *Fixating the shoulder and the elbow simplified the calculation of the eigenvalues of rotational inertia. This constraint, however, does not alter the resulting perceptions when compared with the perceptions achieved through free rotations about any or all of the joints along the arm (Pagano, Fitzpatrick, & Turvey, 1993). The wrist is the preferred joint for calculating rotational inertia because the distance from the centre of mass of the object to the elbow and shoulder may vary continuously during free wielding, resulting in continuously varying rotational inertia. In contrast, the distance from the centre of mass of a firmly held object to the wrist is fixed, resulting in an invariant rotational inertia.*

screen immediately after having grasped the handle of the object. After the child made a decision, the experimenter moved the cursor to the location depicted by the child and demonstrated the behaviour of the mouse. The participants were encouraged to take a short break after each session to avoid fatigue.

Results

The distance from the mouse's initial position to the top of the hill was scaled to the value of 11. The position at which the child stopped the mouse was transformed to a measure of perceived heaviness by taking the distance from this position to the top of the hill. The maximum perceived heaviness, then, was 11 when the participant did not move the mouse, and the minimum perceived heaviness was 0 when the participant moved the mouse all the way to the top of the hill. The mean of the three trials per stimulus was used as the perceived heaviness of that stimulus for that participant.

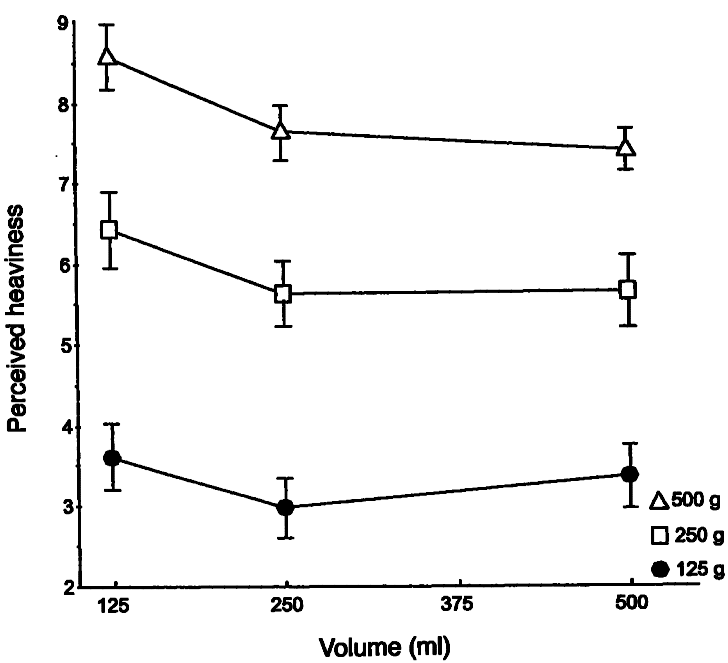

Figure 2. Mean perceived heaviness for each of the nine stimuli.

The mean perceived heaviness values for each of the nine stimuli are shown in Fig. 2. A three-factor analysis of variance (ANOVA) of perceived heaviness as a function of mass, volume, and age was performed (mass and volume were within factors, each with three levels, and age was a between factor, also with three levels). There were significant main effects of both mass ($F(2,30) = 104.92$, $p < .001$), and volume ($F(2,30) = 10.41$, $p < .001$) on perceived heaviness. Consistent with the size–weight illusion, perceived heaviness increased from 3.32 to 7.88 as mass increased from 0.125 to 0.503 kg, and it decreased from 6.21 to 5.47 as volume increased from 125 to 500 ml. The interaction of mass and volume was not significant ($p > .15$). Regarding the effect of age, only the interaction of mass and age was significant ($F(4,30) = 6.04$, $p < .005$),

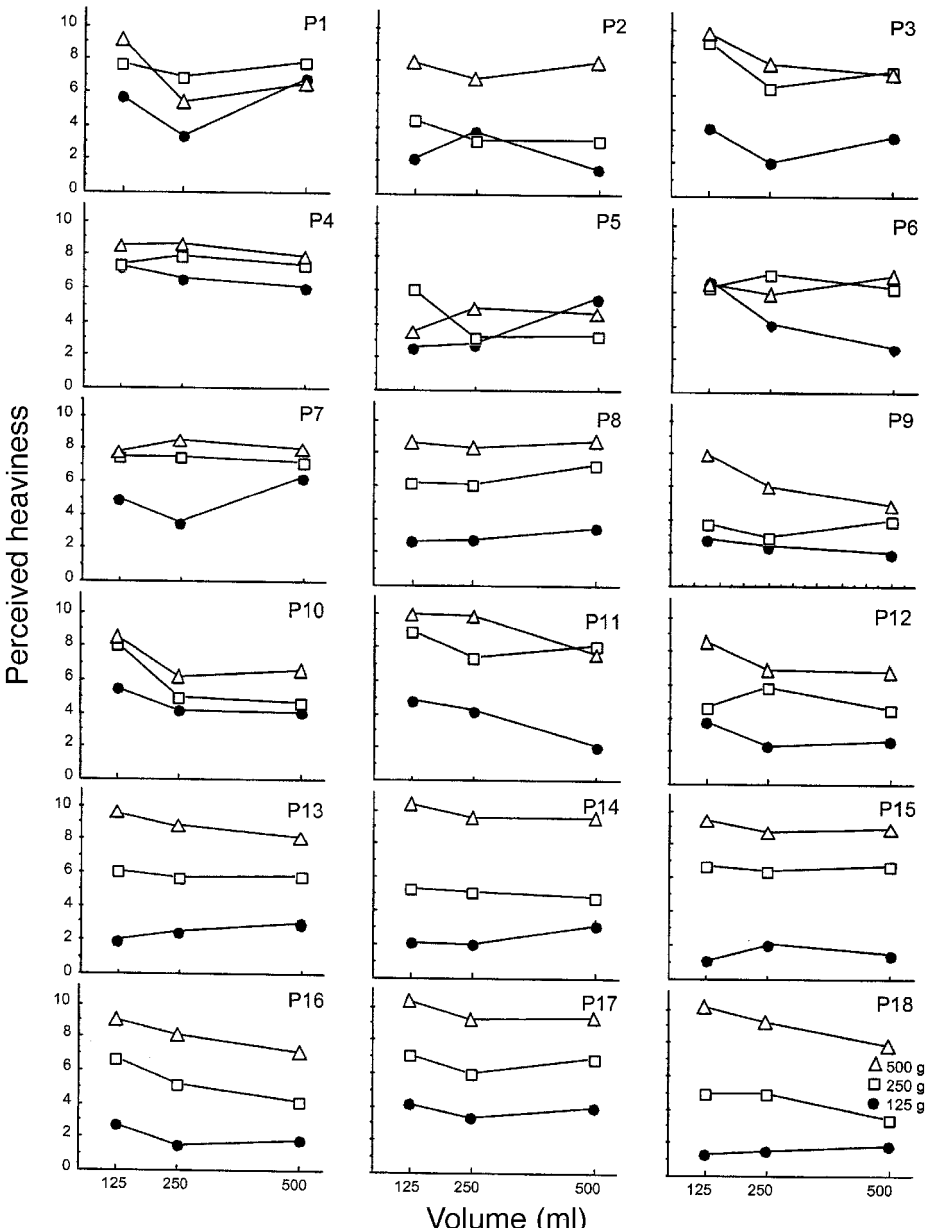

Figure 3. Mean perceived heaviness for each of the nine stimuli for each participant.

older children being more sensitive to changes in mass than young children. The mean perceived heaviness values for each individual participant are shown in Fig. 3. A coefficient of variability for repeated judgments (CV = standard deviation of repeated judgments/mean judgment) was calculated for each stimulus for each participant. An ANOVA with CV as the dependent variable and with the same three factors as above was performed. There was no significant main effect of age ($F < 1$) and no significant interactions with age, (all $ps > .1$). There was no significant main effect of Volume ($p > .1$) and no significant interaction between mass and volume ($F < 1$). The only

Table 2. Results of the power function analysis for each participant

Participant	Age	$R^2(9)$	Exponent (I_1)	Exponent (I_3)
1	3.1	0.675*	0.652	0.340
2	3.1	0.230	0.678	0.535
3	3.3	0.804**	2.359*	1.764
4	3.7	0.735*	2.217*	1.742
5	3.8	0.138	0.006	0.166
6	3.8	0.867**	0.569**	0.471*
7	3.9	0.469	1.352	1.210
8	4.0	0.929**	1.314*	0.66
9	4.4	0.912**	1.979**	1.521*
10	4.5	0.842**	1.691**	1.580**
11	4.8	0.946**	1.848**	1.141*
12	4.8	0.789**	2.609*	2.234*
13	5.0	0.893**	2.055**	1.627*
14	5.1	0.961**	1.956**	1.147*
15	5.1	0.883**	2.673*	1.704
16	5.3	0.944**	3.231**	2.584**
17	5.3	0.966**	1.576**	1.087**
18	5.4	0.970**	3.109**	2.173**

* $p < .05$; ** $p < .01$.

significant effect in this analysis was the main effect of mass ($F(2,30) = 17.67$, $p < .001$), indicating a decrease in CV with an increase in mean perceived heaviness.

Research has shown that adults' perceptions of heaviness can be characterized by a power function in which perceived heaviness scales positively to I_1 and inversely to I_3: perceived heaviness = $(.31)\ I_1^{.36}\ I_3^{-.12}$ (Amazeen & Turvey, 1996)[4]. To test the inertial model of weight perception in the present data, the mean perceived heaviness for each stimulus for each participant was regressed against the first and third eigenvalues of the inertia tensor, all in logarithmic coordinates. The multiple regression revealed significant effects of I_1 and I_3 on perceived heaviness ($R^2(162) = 0.564$, $p < .001$). In logarithmic coordinates, the coefficients on I_1 and I_3 correspond to the exponents on these parameters when the model is expressed as a power function (Coren, Ward, & Enns, 1999). The resulting power function was perceived heaviness = $(10^{-3.242})\ I_1^{1.771}\ I_3^{-1.297}$. The obtained exponents on both I_1 and I_3 were significant at $p < .001$. The 95% confidence intervals for the exponents were from 1.35 to 2.19 for I_1 and from -1.734 to -0.861 for I_3. The standardized coefficients were 2.214 for I_1 and -1.559 for I_3. These findings support the hypothesis that, at the group level, children's reports of heaviness were a function of the rotational inertia of the object

Next, the multiple regression of perceived heaviness on to I_1 and I_3 was performed for each individual participant. The results are presented in Table 2. There was a significant effect of I_1 and I_3 on perceived heaviness for all 5-year-olds, all 4-year-olds, and four of the seven 3-year-olds (ps $< .05$). The observed exponent on I_1 was positive for all participants, with 14 of the 18 being significant at $p < .05$ (all non-significant I_1 exponents were obtained from 3-year-olds only). For 17 of the 18 participants, the observed exponent on I_3 was negative, with 10 significant at $p < .05$ (the non-

[4] *For symmetrical objects, I_2 covaries with I_1 and is thus not included in the equation.*

significant I_3 exponents were from six 3-year-olds, one 4-year-old, and one 5-year-old). These results are consistent with the inertial model of Amazeen and Turvey (1996), who found a positive exponent on I_1 and a negative exponent of smaller magnitude on I_3. A notable difference, however, is that both exponents from the present analysis are of a greater magnitude than those found previously in an adult population.

In summary, perceived heaviness was a function of mass and volume consistent with the size–weight illusion. Older children were more sensitive to differences in mass than younger children. Perceived heaviness was predicted by a power function similar to that established for adults, I_1 and I_3 being significant predictors for most of the children.

Discussion

This study investigated preschoolers' ability to perceive the heaviness of objects that are occluded from view. The participants were asked to hold the objects by a handle and to make judgments on their heaviness. The nine objects differed in mass and volume. Despite the fact that the children could neither see the stimuli nor enclose the stimuli in their hands, there was an effect of volume on the perception of heaviness consistent with the size–weight illusion—perceived heaviness decreased with increased volume. The results showed that children, like adults, scale their perceptions of heaviness not to mass or volume, but to the rotational equivalent of mass, rotational inertia.

Dynamic touch and size–weight illusion in preschoolers

The preschoolers in the present study were able to use dynamic touch to report the heaviness of objects. This extends Fitzpatrick's (1998) finding that preschoolers were able to determine the length of an unseen rod simply by grasping and wielding. Children in that study were almost as precise as adults in reporting the length of the rod, with older children being more accurate than younger children. The results of Fitzpatrick (1998), combined with the results of the present experiment, indicate that dynamic touch is a natural mode of perceiving for preschool children. The fact that preschool children can readily perceive both length and weight by dynamic touch further suggests that they may also use dynamic touch to perceive the other object properties that adults perceive by dynamic touch, such as, width, length, volume, shape, location of grasp, and limb orientation (Turvey & Carello, 1995).

Not only do preschool children use dynamic touch in perceiving weight, but they are also subject to the same size–weight illusion in dynamic touch as adults. Their perception of heaviness of unseen objects lifted by a handle was a function of mass and volume. As volume increased, objects were perceived as being lighter. This illusion has previously been demonstrated in children, but only with combinations of vision and haptic touch (Holmberg *et al.*, 1968; Pick & Pick, 1967; Robinson, 1964). The present experiment is the first demonstration of a size–weight illusion by dynamic touch in preschoolers.

Rotational inertia and intermodal integration

Children in the present study scaled their reports of perceived heaviness to rotational inertia. Their perceived heaviness followed the same pattern that has been established

for adults (Amazeen, 1997, 1999; Amazeen & Turvey, 1996). Children's perceived heaviness scaled positively to I_1 and inversely to I_3. However, children differed from adults in that the magnitudes of the exponents of I_1 and I_3 for children were greater than those found for adults. Such a finding is consistent with Stevens' (1960, 1970) assertion that exponents of smaller magnitude reflect a smaller range of stimulation to which the participant is sensitive.

Although the hypothesis of intermodal integration and percept–percept coupling was not specifically tested in the present experiment (as it was in Amazeen, 1999 and Pick & Pick, 1967), the findings of this study do support and extend the conclusions of Pick and Pick (1967) regarding intermodal integration. The size–weight illusion in the present study resulted from children's sensitivity to a single stimulus property (i.e. rotational inertia) that integrates mass and volume. This suggests that the size–weight illusion can be explained without assuming a process of mental integration. In fact, the perception of size is not necessary for the size–weight illusion. Rather, the physical volume of an object exerts its influence on perceived heaviness through the stimulus property to which perceived heaviness is scaled. It exerts its influence through rotational inertia. Given that rotational inertia is a function of both mass and volume, the perception of heaviness (based on rotational inertia) may also appear to be a function of mass and volume. Hence, perceived heaviness need not be based on a percept–percept coupling (Ashby & Townsend, 1986; see also Amazeen, 1999).

Individual differences

Although there were significant effects of rotational inertia on perceived heaviness when considering group data, there were differences across the age range in the present study. As depicted in Fig. 3 and Table 2, not all children demonstrated the size–weight illusion. In fact, for some children, there were no discernible effects of volume or rotational inertia. Although there was no significant interaction between age and volume, the rotational inertia analysis shows that all non-significant regression models pertain only to the 3-year-old children. These children did not show a significant effect of I_1 and I_3 on perceived heaviness.

A similar age effect was reported by Fitzpatrick (1998). Fitzpatrick suggested that the weakened dependence on rotational inertia in 3-year-old children might be the result of a lack of precision, rather than a lack of ability to use dynamic touch for perception. The same conclusion could be applied to the present findings. While the effect of rotational inertia failed to reach significance in many 3-year-old children, there were (non-significant) positive effects of I_1 and inverse effects of I_3 for most of those children. It appears that 3-year-old children are beginning to develop the sensitivity seen in older children and adults, but they have yet to develop the necessary precision.

Conclusions

Children as young as 3 years of age were successful in perceiving the heaviness of objects by using the sensory system of their muscles and joints. They were sensitive to the rotational resistance of an object, a property that is a function of the volume and mass of the object. This sensitivity may explain the size–weight illusion without making reference to a cognitive process of intermodal integration.

Acknowledgements

Heidi Kloos is now at the Department of Psychology, University of Massachusetts. The authors would like to thank the children, parents and staff of the Child Study Laboratory for their participation in and help with this project, and Nicole Bray and Richard Barinbaum for their assistance in data collection. Furthermore, they would like to thank Flavio DaSilva for programing the Mouse Game.

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Received 23 October 2000; revised version received 6 July 2001