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Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 30(30)

ISSN
1069-7977

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Publication Date
2008

Peer reviewed

Will it float?
How Invariance Affects Children's Understanding of Object Density

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Abstract

The density of materials and objects is an important topic in physics instructions. However, the extent to which children naïvely understand this concept is still unclear. Some findings suggest that children cannot differentiate between an object's mass and its density, whereas other findings show competent density performance even in preschoolers. The goal of the current study is to bridge these conflicting results. The specific hypothesis is that children can distinguish among different densities if – and only if – density is an invariant property in the set of stimuli. Data with 2- to 6-year-olds and adults provide support for this hypothesis. Children 4 years and older, as well as adults, were affected by the distribution of density in the set of objects presented to them, in that they could tune into density spontaneously when density was invariant, and less so when mass and volume were invariant. Theses results have important implications for our understanding of children's problem solving, as well as on how the concept of density could be taught to young children.

Keywords: preschoolers; naïve physics; cognitive development; task context; reasoning.

Introduction

Density is an intensive property of materials, quantifiable as an object's mass over its volume. In simple terms, the more mass is packed into a volume, the denser the object is. Density affects the behavior of objects in crucial ways, most notably in relation to objects' buoyancy. An object that is less dense than water will float, while an object denser than water will sink. And among sinking objects, the denser object will sink faster than the less dense object (assuming the shape stays the same). Given these practical applications, the concept of density is often a standard unit in physics instruction.

Yet, teaching children about density is not as successful as one might hope. Even 12-year-olds tend to ignore explicit demonstrations, for example about sinking objects, in favor of their pre-existing beliefs about how mass and volume should affect objects' sinking behavior (e.g., Hewson & Hewson, 1983; Penner & Klahr, 1996). Clearly, children tend to hold onto their naïve beliefs about physical relations, ignoring classroom interventions (e.g., McDermott & Redish, 1999; Pfundt & Duit, 1991; Schauble, 1990). The current study looks at what exactly is it that children naïvely know about the concept of density.

Naïve Understanding of Density

A variety of methods have been used to study children's naïve understanding of density. In Piaget's classical studies, children were presented with a variety of household objects, including metal utensils, candle wax, and tin foil, and they were asked to predict whether an object would sink or float (Inhelder & Piaget, 1958). Other methods include presenting children with pairs of blocks and asking them to determine the heavier kind of stuff (e.g., Smith, Carey & Wiser, 1985), or to ask them to predict the faster sinking object (e.g., Penner & Klahr, 1996; Kloos & Van Orden, 2005).

Most findings suggest that children have pronounced difficulty with the concept of density. From preschool age to adulthood, participants seem to ignore differences in objects' density and instead respond in terms of an object's mass. These findings led to the well-known claim that children cannot differentiate between mass and density (Smith et al., 1985). A way of alleviating this problem and help students differentiate between mass and density would then be to demonstrate that mass and density have unique outcomes.

However, there are some findings that show density competence even in preschool children. Most notable is Kohn's (1993) study because it used a widely common method: Participants had to determine whether an object would sink or float. No feedback was provided, and no object was ever placed in water during the experiment. Yet, 4-and 5-year-olds performed better than what would be predicted by chance alone (see also Kloos & Van Orden, 2005).

Explaining Discrepant Results

How can these conflicting findings be reconciled? A common way is to postulate the existence of two different types of knowledge, an implicit kind of knowledge and an explicit kind of knowledge. A task that yields successful performance might tap into implicit knowledge, while a task that yields unsuccessful performance might tap into (the lack of) explicit knowledge. Children might have an implicit understanding of density, but not an explicit one (e.g., Kohn, 1993).

Yet, this explanation does not only have theoretical problems of testability and generalizability, it also has practical problems of applicability. Claiming that children have an implicit understanding of density, but not an explicit one, provides little information about what might be a successful instructional approach. Can instructors take advantage of something like children's implicit knowledge of density? And why do commonly used instructional approaches fail?

The current study tests an alternative explanation for what might cause the discrepant findings in children's naïve understanding of density. It is based on the idea that children's performance, rather than merely reflecting their knowledge (or the lack of), reflects their interaction with the immediate task context (Gigerenzer & Richter, 1990; Kloos & Van Orden, 2008). Children's predictions about the faster sinking object, for example, might be a function of what kinds of objects children are presented with.

These ideas are anchored in basic-research findings about categorization and learning (e.g., Smith, Jones, & Landau, 1996; Sloutsky, 2003). Children and adults quickly detect correlational patterns in the immediate task context and make use of it in their performance. More specifically, they detect how features are distributed in the set of objects and base their categorization judgment on what they perceive as the *invariant* property. Differences in performance (such as those described above with the concept of density) might therefore be due to differences in structural properties of the task, rather than due to what children know about the specific concept.

Invariance in Density Tasks

The invariant property in a set of objects pertains to a feature that allows for most systematic performance. In a categorization task, for example, the invariant property is the feature that divides objects most reliably into two categories. In a feedback task, the invariant property is the feature that stays the same across trials (and thus allows for correct performance).

A variety of findings have shown the importance of invariant features in perception and action (e.g., Runeson, Juslin & Olsson, 2000). More importantly, invariance was also shown to affect adults' categorization (e.g., Crawford, Huttenlocher & Engebretson, 2000; Huttenlocher, Hedges & Vevea, 2000). When asked to estimate the size of a figure that was presented to adults but then disappeared from view, their errors were systematically related to the distribution of size in the entire set of figures. This was the case even though participants never saw (or were asked to pay attention to) the entire set of figures juxtaposed. Adults automatically kept track of how the figures varied in size.

Could children be sensitive to the distribution of density in a set of objects? Suggestive evidence comes from research with neonates on their understanding of numerosity (Antell & Keating, 1983). Newborn infants were presented with a set of visual stimuli, each showing an array of dots. In a habituation/dishabituation looking paradigm, children were first presented a specific number of black dots (e.g., two dots). That is to say, arrays differed in a variety of features (e.g., distance between dots, size of dots), with the number of dots being the invariant property. During dishabituation, children were shown an array of a new number of dots (e.g., three dots). Children's looking pattern suggested that these very young children dishabituated (i.e., they regained attention) to the new number. They were able to ignore the varying features and tune to the invariant feature of number.

The same process of extracting the invariant property from the set of stimuli may have taken place in Kohn's (1993) study, when children were asked to predict whether an object would sink or float. Recall that findings in Kohn's study are in stark contrast with other density study: Even preschoolers could ably distinguish objects in term of their density. Indeed, the set of stimuli used in Kohn's study differed markedly from studies that show density difficulties. Uniform cubes were created that differed in mass and volume in many small increments, while they differed in density in few and large increments. Being presented with a categorization task, neither mass or volume served as a reliable invariant property. Cubes differed on six levels of mass (and on five levels of volume), with no clear distinction between heavy and light cubes (or between large and small ones). Density, on the other hand, was invariant: half of the objects had a density below that of water, and half of the objects had a density above that of water.

Like in the adult judgment tasks described above (Crawford et al, 2000; Huttenlocher et al, 2000), children in Kohn's task never compared objects side by side. This made it difficult for children to differentiate objects in terms of their mass and volume, and it might have helped children assess the distribution of the invariant feature density. In contrast, studies that show difficulty with the concept of density present children with pairs of objects that differ markedly in mass and volume. In such a pair-situation, mass or volume becomes the invariant property. Children can distinguish and hence categorize objects in terms of their mass, for example). Density being a feature that can be detected only across distributions becomes hidden in such a pair task.

In sum, it seems plausible that children might base their physics judgment on the invariant property of the experimental stimuli. They might perform well when density is the invariant property of the set, compared to condition in which this is not so. The current study tests this possibility explicitly.

Overview

The goal of this study was to test the effect of feature distribution on children's and adults' naïve understanding of density. Two within-subjects conditions were contrasted that differed in how objects were arranged. In particular, in the *density* condition, children were presented with one object at a time, the set of which had density as the invariant property. Conversely, in the *mass\volume* condition, children were presented with pairs of objects that differed in mass and/or in volume (as well as density), making mass and volume invariant properties. In both conditions, participants could manipulate the objects for as long as they like, after which they had to decide whether an object would sink or float.

To obtain a developmental progression in children's naïve understanding about density, participants included 2- to 6-year-olds as well as adults. The prediction was that children will be sensitive to the differences in density sometime during preschool age (in line with Kohn's findings), and that participants will perform better in the density than the mass\volume condition.

Method

Participants

Children were recruited from suburban middleclass preschools, and adults were recruited from the subject pool of Introduction to Psychology classes at the University of Cincinnati. Adults received course credit in return for their participation. The final sample consisted of 7 2-year-olds (5 girls and 2 boys; *M* = 31.7 months, *SD* = 2.6 months), 9 3-year-olds (3 girls and 6 boys; *M* = 41.6 months, *SD* = 3 months), 10 4- to 6-year-olds (6 girls and 4 boys; *M* = 65.1 months, *SD* = 11.7 months), and 11 adults (6 women and 5 men; *M* = 20.2 years, *SD* = 2.4 years).

Stimuli

Ten wooden cubes were created that differed along mass and volume, as shown in Table 1.

Table 1: Dimensions of Cubes (with volume given in cm^3)

	Density	
Mass (g)	2 g/cm^3	0.5 g/cm^3
30		64
48		104
77	39	166
123	64	262
197	104	405
314	166	
503	262	

As can be seen from Table 1, the ten cubes comprised of seven masses (ranging from 30 g to 503 g) and six volumes (ranging from 39 cm^3 to 405 cm^3), but only two densities (one being about 2 g/cm^3, and one being about 0.5 g/cm^3). Objects with a density of 2 g/cm^3 sink in water (water having a density of 1 g/cm^3), while objects with a density of 0.5 g/cm^3 float. Note that cubes were constructed in such a way that neither mass nor volume was predictive of the cube's sinking behavior. For three masses (77g, 123g, and 197g), cubes of the same mass could sink or float. And for four volumes (64 cm^3, 104 cm^3, 166 cm^3 and 262 cm^3), cubes of the same volume could either sink or float.

Cubes were hollowed out and filled with lead and wood putty until the desired mass was obtained. Care was taken to distribute mass as equally as possible throughout a cube. Once the cube was filled and closed, it was painted in bright colors, identical across cubes.

Stimuli were identical across the two conditions, with only the arrangement of cubes changing as a function of condition. In the density condition, cubes were presented to participants one at a time, because density was the invariant property in the entire set of objects. Conversely, in the mass\volume condition, cubes were arranged into pairs in such a way that mass and/or volume varied within a pair (in addition to density). The cubes that were combined into a pair are connected with a line in Table 1. Note that each pair consisted of a sinker and a floater, with the sinker always being the lighter and/or smaller of the two cubes. In other words, density was pitted against mass within a pair. The rationale was to create a setting in which both mass and density could form the basis for categorization judgment. Pitting mass against density made is possible to determine whether children focus on mass or on density in their decision on whether a cube would sink or float.

Procedure

The experiment was administered on a computer and controlled by SuperLab Pro 2.0 software. Participants were tested in a quiet room (either in their preschool or in the lab) by female hypothesis-blind experimenters.

The cover story involved a character named Wump who found some special rocks on a far-away planet and now wants to know if the rocks would sink or float in earth water. Note that throughout the experiment, there were no practice trials, and no cube was ever placed in water.

The two conditions were administered in a within-subject design, with the mass\volume condition always being presented first. This is because better performance was predicted in the density condition when participants had to extract the invariant property density from the entire set of stimuli. Given that participants were not provided with any feedback, possible learning effects from the mass\volume condition to the density condition were unlikely. Conversely, were the density condition presented first, children extracting the invariant property of density might have inflated their performance in the ensuing mass\volume condition.

During the first part of the experiment (mass\volume condition), participants were presented with the five unique pairs of cubes, one pair at a time, in random order, with each pair being presented twice (for a total of 10 trials). Within a trial, the two cubes were placed into the participants' hands in random left-right arrangement, and he or she was encouraged to feel them. Participants had to decide for each cube whether it would sink or float. The prediction for this condition is that participants will perform below optimal, their judgment being affected by misleading differences in mass.

During the second part of the experiment (density condition), participants were presented with the ten unique cubes, one cube at a time, in random order, with each cube being presented twice (for a total of 20 trials). Within a trial, the cube was placed in front of the participant, and he or she had to decide whether it would sink or float. Having cubes presented one at a time allowed participants to base their judgment on how features are distributed across the entire set of cubes (as opposed to across a pair of objects). As argued above, the only invariant property across the entire set of objects is density. It is therefore expected that participants perform better in this second part of the experiment.

Note that no feedback was provided during the entire duration of testing. This rules out the possibility that improved performance across trials could be due to learning.

Results

Performance was scored in terms of whether a cube was identified correctly as a sinker or floater or not (i.e., the floater was determined to be a sinker, or vice versa).

Preliminary analyses pertained to performance on individual pairs of cubes (mass\volume condition) and on individual cubes (density condition) to determine whether any particular pair of cubes (or any particular cube) was more difficult than another. Two one-factor ANOVAs, one for pairs (with levels being the unique pairs), and one for individual cubes (with levels being the unique cubes), revealed no significant difference on mean proportion of correct performance (*p*s > 0.33). These findings suggest that any effect of condition or age group is not driven by performance on an individual pair of cubes, or on an individual cube.

Figure 1 shows the mean proportion of correct performance as a function of age group and condition. A 2-by-4 mixed design ANOVA was conducted with condition as the within-subject factor and age group as the between-subject factor. It revealed a significant main effect of age, $F(3, 31) = 3.4$, $p < 0.03$, with older children and adults ($M = 0.81$, $SE = 0.04$) performing better than the younger children ($M = 0.66$, $SE = 0.05$). Notably, 2-year-olds did not perform better than what would be predicted by chance, single-sample $t(6) = 0.89$, $p > 0.8$), while participants 3 years and older performed above chance across condition, single-sample ts > 3.3, $p < 0.05$.

More importantly, the ANOVA revealed a significant interaction, $F(1, 31) = 2.8$, $p < 0.05$, with older children and adults, but not younger children, performing differently as a function of condition, paired-sample ts > 2.5, $p < 0.05$. In other words, children 4 years and older as well as adults were affected by the manipulation of how the cubes were arranged. Even though these participants were presented with the very same cubes during the density condition and the mass\volume condition, they performed better when they were presented with cubes one at a time than when they were presented with pairs of objects.

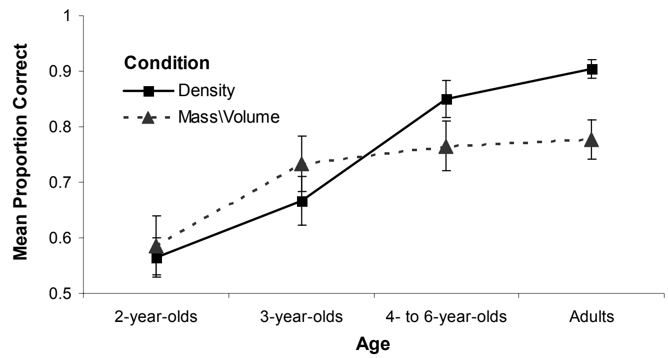

Figure 1: Mean accuracy of participants' performance as a function of age and condition. Chance performance is at 0.5. Error bars represent standard errors.

To assess whether the difference in performance between condition is due to having to make a judgment about one vs. two cubes, a new group of 4- to 6-year-olds was tested with pairs only ($n = 10$; 5 girls and 5 boys; $M = 63.2$ months, $SD = 10$ months). For *critical* pairs (identical to the ones used in the mass\volume condition above), mass and volume were pitted against density, in that the lighter and smaller cube was the denser one. Conversely, for *non-critical* pairs, the heavier cube was also the denser one. The task was identical to the mass\volume condition above, with children being presented with 10 critical and 10 non-critical pairs in random order.

Results show a significant difference between pair types, paired-sample $t(9) = 4.3$, $p < 0.05$, which children performing better with non-critical pairs ($M = 0.82$, $SE = 0.06$) than with critical ones ($M = 0.71$, $SE = 0.06$). This finding rules out the possibility that the difference in condition reported above is driven by the superficial difference in having to made a judgment about one vs. two cubes.

Discussion

The goal of the current study was to test whether young children's naïve understanding of density is affected by the immediate task context in which children act. Of particular interest was the degree to which the distribution of features in the stimuli matters in children's task performance. The speculation was that children can successfully tune into differences in density when density is the invariant property in the set of objects – that is, when differences in density yield clear categories. Conversely, children were expected to base their judgment on mass and volume when differences in these features – rather than in density – were made salient.

The results confirm the speculations. To sum them up, 4- to 6-year-olds and adults performed better when density was the only invariant property (mass and volume could not be juxtaposed), than when the objects differed saliently in mass or volume. In the latter case, while still showing above chance performance, their judgment was anchored by differences in mass and volume.

Could the difference in performance between conditions be explained by extraneous factors such as fatigue, practice, or attentional demands? This is not likely, for the following reasons. First, as discussed above, children were not given any feedback during the task, ruling out the possibility of practice. Second, 3-year-olds performed above chance in both the density and the mass\volume condition (with no difference between conditions). Extraneous factors such as fatigue should have affected the younger children more than the older children. Yet, finding above chance performance in the younger children with no change in condition rules out this possibility. Finally, the results obtained with a second group of preschoolers rule out the possibility that the mass\volume condition had a higher attentional demand than the density condition. These children performed worse in the mass\volume condition than a condition with similar attentional demands that did not pit mass differences against density.

Implications for Education

The larger goal was to bridge conflicting results on children's naïve understanding of density as a means of improving instructional methods. Rather than having to postulate an implicit vs. explicit type of knowledge to account for discrepancy in children's competence, the current results provide a viable alternative with important implications for education. They suggest that children's difficulty with density are tied to a task context in which objects can be compared in terms of mass and volume. Once objects differ saliently in mass and volume, children might use these features are anchor points – as invariant properties – to make systematic judgments. Indeed, teaching methods that emphasize mass and volume are rather unsuccessful at teaching children about the concept of density. Conversely, being presented with objects that differ saliently in density might allow children to gain an intuitive senses of the relevant physical property, after which a more formal understanding might be construed (cf., Smith, Maclin, Grosslight & Davis, 1997; Smith, Snir, & Grosslight, 1992).

Of course, the findings do not pertain merely to density but can be extended to learning of other the physical concepts and knowledge development in general. Rather than treating knowledge as a static entity, the current results demonstrate the importance of the immediate task context in children's judgment. They shows that children are engaged in an active sense-making of the immediate task context that is controlled by simple attention to structure.

Acknowledgments

The author thanks Ahn Thu Inman, Adrienne Frazier, and Daniel Baum for help with the stimuli, and Anna Silverman, Becky Fenstermaker, and Cathy Odar for their help with data collection. This work was supported by a grant from the National Science Foundation (DRL # 723638) to the author.

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