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Situated Naïve Physics: Task Constraints Decide what Children Know about Density

Heidi Kloos^a, Anna Fisher^b, and Guy C. Van Orden^a

^aCenter for Cognition, Action & Perception; Department of Psychology; Univ. of Cincinnati

^bDepartment of Psychology; Carnegie Mellow Univ.

Abstract

Children's understanding of density is riddled with misconceptions – or so it seems. Yet even preschoolers at times appear to understand density. This article seeks to reconcile these conflicting outcomes by investigating the nature of constraints available in different experimental protocols. Protocols that report misconceptions about density used stimulus arrangements that make differences in mass and volume more salient than differences in density. In contrast, protocols that report successful performance used stimulus arrangements that might have increased the salience of density. To test this hypothesis, the present experiments manipulate the salience of object density. Children between 2 and 9 years of age and adults responded whether an object would sink or float when placed in water. Results indicated that children's performance on exactly the same objects differed as a function of the saliency of the dimension of density, relative to the dimensions of mass and volume. These results support the idea that constraints – rather than stable knowledge – drive performance, with implications for teaching children about non-obvious concepts such as density.

Situated Naïve Physics: Task Constraints Decide what Children Know about Density

A naïve mind appears riddled with misconceptions – overly simple ideas about the world that were not explicitly taught. Misconceptions exist about biology, astronomy, chemistry, and physics, to name just a few domains, and they exist among a wide range of individuals, including infants, preschoolers, high-school students, college students, and adults¹. Yet, the nature of misconceptions is still debated. Why, for example, do children and adults mistakenly equate the density of a block with its heaviness? Are there cognitive limitations when it comes to differentiating density from heaviness? Or is ordinary exposure to the consequences of density (e.g., sinking vs. floating) too limited? Or are there other reasons altogether?

The argument put forward in this paper is that misconceptions originate in the competition among immediately available constraints (cf. Kloos & Van Orden, 2009, in press; Van Orden & Kloos, 2005). The term *constraint* refers to a relation between actor and task that

Please address correspondence to Heidi Kloos, Department of Psychology, University of Cincinnati, 230 Dyer Hall, Cincinnati, OH 45221-0376, Phone: (513) 556-5525, Fax: (513) 556-1904, heidi.kloos@uc.edu.

¹Example references include: Chinn & Brewer, 1993; Dunlop, 2000; Eryilmaz, 2002; Ferrari & Chi, 1998; Flavell, 1999; Gopnik & Meltzoff, 1997; Gelman, & Raman, 2002; Kerr & Walz, 2007; Krist, Fieberg, & Wilkening, 1993; Mazens & Lautrey, 2003; McKinnon & Geissinger, 2002; McKinnon, Geissinger, & Damaia, 2002; Mikkilae-Erdmann, 2001; Nakhleh, 1992; Nguyen, & Rosengren, 2004; Oezay & Oeztas, 2003; Pine, Messer, & Godfrey, 1999; Pine, Messer, & John, 2001; Riemeier & Gropengiesser, 2008; Springer, 1995; Van Dooren, De Bock, Hessels, Janssens, & Verschaffel, 2004; Wellman & Gelman, 1992; Wilkening & Martin, 2004; Yip, 1998.

changes the available degrees of freedom for task responses (Bernstein, 1967; Flach, Dekker & Stappers, 2007; Smith, Thelen, Titzer, & McLin, 1999; Turvey, 1990; Turvey & Carello, 1981). Constraints are neither a reflection of the task protocol alone, nor are they a reflection of the capacities of the actor alone. In other words, performance is neither a mere reflection of the environment, nor is it a half-silvered mirror on the actor's mental structures. Instead, it is the coming together of the immediate task context and an actor's prior history, which reduces the available options leading to a particular performance.

Take, for example, a task in which a child searches for a toy hidden in one of two locations: A or B (Piaget, 1963). Factors that determine the location at which the child would search include the task instructions, the attractiveness of the toy, and the child's capacity to remember where the toy was seen last. Other – less obvious – factors include the spatial distance between the two hiding places A and B, the temporal delay between hiding and searching, the details of the hiding events, changes in the child's coordination of reaching, and probably many others (e.g., Smith, Thelen, Titzer, & McLin, 1999). The immediate relations among all these factors constitute the constraints on the child's performance at a given time.

The constraints view has implications for the study of misconceptions, far beyond a mere acknowledgment that a task context can affect a child's performance. First, this view presupposes interdependence between a child's environment and mental constructs. Like woven threads that become cloth, “knowledge is fundamentally a coproduction of the mind and world, which like a woof and warp need each other to produce and to complete an otherwise incoherent pattern” (Hung, 2002; p. 394). In other words, knowledge and task are not separate causal factors but mutually codetermining factors of a child's performance. As a consequence, it is not possible to empirically isolate specific mental structures or deficiencies that might elicit misconceptions (e.g., a competence that is yet blind to differences between density and heaviness). Neither knowledge nor the lack of it can be isolated empirically. Instead, misconceptions – like every cognitive performance – entangle the factors that underlie the expressed misconception. Successful and unsuccessful performances both entail the relevant congruent and opposing constraints present in a “knowledge” response.

Second, an emphasis on constraints makes unique predictions about how to support veridical understanding and conceptual change. It underscores the importance of aligning task constraints so as to favor veridical performance from the beginning. In contrast, a conventional way to correct a misconception is to create a task context in which mistaken performance is elicited first (e.g., Kloos & Somerville, 2001). The idea of such an approach is to change a misconception by highlighting its shortcomings through juxtaposition. However, giving priority to the mistaken performance might, in fact, be counterproductive if it increases the salience and possible coherence of constraints that support making an error. Instead a child may be made less susceptible to irrelevant features of the task if the task context reliably tips the balance of constraints in the direction of veridical performance.

Before these ideas can be explored, the importance of immediately available constraints needs to be demonstrated empirically. With this goal in mind, we focus on children's misconceptions about object density.

Misconceptions in Density Tasks

Material density is defined by the ratio of an object's mass over volume. Therefore, any manipulation of density is also a manipulation of the relation between mass and volume, neither of which predicts density by itself. It is commonly assumed that density has to be inferred from the relation of mass to volume, making density something of a hidden feature,

compared to the more obvious features of mass (e.g., heaviness) or volume (e.g., size). This is one reason that density is a concept covered in school (e.g., Ohio Academic Content Standards, 2009), making it relevant for investigation.

Tasks that test for understanding of density often involve scenarios in which variations in density are pitted against variations in mass and volume (e.g., Kloos & Van Orden, 2005; Smith, Carey & Wiser, 1985). In these scenarios, children are presented with a pair of objects for which the heavier object has the lower density. In these task contexts, children perform poorly (cf., Piaget, 1963; Smith et al., 1985; Hewson & Hewson, 1983; Penner & Klahr, 1996). For instance, Smith et al. (1985) reported that 80% of 3-year-olds, 70% of 4-year-olds, 81% of 5-year-olds, and 62% of 6- to 7-year-olds incorrectly concluded that a less dense object was made out of heavier kind of stuff. And when an aluminum block was heavier than a steel block, only 33% of 8- to 9-year-olds could categorize the blocks correctly on the basis of density.

Such findings have been taken to suggest that children start out with some mistaken idea about density, maybe that density is equivalent with mass (cf. Carey, 1985). Nonetheless, there are also reports of competent density performance in young children. Most notable is Kohn's (1993) study, in which children responded whether objects would sink or float. No feedback was provided, and no object was ever placed in water. Yet, even preschoolers performed above chance when they had to distinguish among sinkers and floaters, without being misled by mass or volume. Similar success was reported in a steel-and-aluminum sorting task used in the Smith et al. (1985) study mentioned above. Proportion of incorrect responses, for the exact same objects, was cut in half when objects were judged one by one, rather than in pairs pitting mass against density.

One explanation of this apparent contradiction is that successful performance may stem from an implicit, rather than an explicit, understanding of density (Kohn, 1993). Another explanation is that children are more successful on less complex tasks than on more complex tasks (Smith et al., 1985). Both of these explanations assume the primacy of knowledge about mass and volume over density. But this assumption is difficult to reconcile with instances where people fail to ignore density, even with explicit instructions to do so. For instance, when presented with two equally heavy objects that differ in size, children and adults judge the bigger object as being heavier than the smaller object, a finding known as the size-weight illusion (Pick & Pick, 1967; Robinson, 1964; Stevens & Rubin, 1970). In particular, because a heaviness judgment requires the participant to lift the object, and thus to rotate it around a rotating joint (the wrist, the elbow, or the shoulder), perceived heaviness is determined by the object's rotational inertia, which is a function of object density (Amazeen & Turvey, 1996; Kloos & Amazeen, 2002). Apparently, some task conditions make it difficult to perceive heaviness without density intrusions; yet other task conditions make it difficult to perceive density without heaviness intrusions.

Constraints on Density Performance

As we suggested above, stable repeatable performance – rather than reflecting stable misconceptions (or stable veridical knowledge, for that matter), reflects a stable configuration of constraints in the relations between participant and task. That is to say, misconceptions are neither necessarily a reflection of different types of knowledge (implicit vs. explicit knowledge) nor a reflection of different cognitive demands (easy vs. difficult tasks). Instead, both successful and unsuccessful performances might reflect the tipping point of a ratio of opposing constraints (for a review, see Van Orden, Kloos, & Wallot, 2009). If so, then what constraints are prominent in performing density judgments?

Density tasks involve category judgments (e.g., ‘does it sink or float’; ‘which one is made of the heavier kind of stuff’). Non-obvious constraints in this case might be supplied, in part, by the relative salience of features that vary in the task context². Indeed, in tasks that elicited successful density performance, mass, volume, and density were distributed across objects in a way that made it difficult, if not impossible, to compare objects on any dimension other than density. For example, in Kohn’s (1993) study, children were never given an opportunity to compare objects side by side, and differences in mass or volume were never brought to children’s attention. Conversely, in tasks that elicit unsuccessful density performance, children were either explicitly encouraged to focus on mass and volume in isolation (e.g., by asking children to point to the heavier of two objects), or objects differed in many salient properties other than density, including shape, function, and color (Piaget, 1963). Thus, the latter task contexts were such as to maximize constraints that favored a focus on properties other than density.

This difference in how tasks were implemented – rather than an implicit vs. explicit density understanding (or high vs. low cognitive demand) – could account for the differences in density performance discussed above. The experiments we report here tested this hypothesis explicitly. Does a non-obvious manipulation of constraints change the apparent knowledge children exhibit in density tasks? We hypothesized that salience of object properties determines whether a child performs correctly – even for the exact same objects.

One intuitive way to manipulate salience of objects properties would be to manipulate the distribution of mass and volume factorially with the distribution of density. However, given that density is a ratio of mass and volume, any variations in density are also variations in mass or volume. It is therefore not possible to construct a within-object factorial manipulation. Instead we manipulated presentation conditions and how object properties were distributed across the set of objects that were presented to participants. A set of cubes was constructed such that half of the cubes had one density (they floated), and the other half of the cubes had another density (they sank). Mass and volume, on the other hand, varied incrementally, such that there were seven different levels of mass and six different levels of volumes. Adjacent values of mass and volume increased in relatively small increments (i.e., approximately 60%), compared to the single increment of density (i.e., 400%). As a result of this manipulation, variations in density demarcate a category (e.g., floaters vs. sinkers), whereas neither variations in mass nor variations in volume could function as clear category marker. Therefore, across the entire set of cubes, each cube presented one by one, density is likely to be the most salient dimension in a context in which category membership needs to be determined.

Contrast such one-by-one presentation of cubes with presenting the same cubes in pairs. Table 1 shows possible combinations of object in schematic form. Using the symbolism of Smith et al. (1985), the heavier object in a pair is underlined, and the denser object has the darker outline. Pairs of objects could differ in mass and density (Combination 1), in volume and density (Combination 2), in mass and volume (Combination 3), or in all three dimensions (Combinations 4–5). In pairs that differ in density as well as in mass or volume, density is no longer the only dimension that functions as a category marker. That is to say, salience of density as category marker in a pair trial is reduced with respect to salience of mass or volume as category maker, at least so long as mass is pitted against density within a

²Note that salience – like any constraint more generally – is never a function of task context alone, nor is it a function of a person’s history alone. Even very large changes in a task context will be ignored if the actor’s propensities to perform are not aligned with the changes in the task context. For example, adults instructed to focus on the ball handling in a basketball game will fail to notice a man in a gorilla suit pounding his chest on the basketball court (Simons & Chabris, 1999). And vice versa, even a tiny change in a task context can affect performance if the learner has become attuned to the relevant dimensions, as documented in numerous instances of perceptual learning (Gibson, 1963; Hall, 1991).

pair. Therefore, unless mass and density are correlated positively, density will be less salient in paired presentations than when cubes are presented one by one. The goal of Experiment 1 was to test whether such a difference in the salience of density affects children's performance on density tasks.

EXPERIMENT 1

As in Kohn's (1993) study, participants were asked to predict whether cubes would sink or float in water. Unlike previous research, however, we changed the experimental protocol to manipulate the salience of object density. For *pair-presentation* trials, objects appeared in pairs for which density was not a salient category marker. In particular, mass was either held constant, while volume and density varied (Combinations 2 in Table 1), or mass and volume were pitted against density (Combination 4 in Table 1). For *single-presentation* trials, the same objects were presented one by one, as part of a larger set of objects for which density was the more salient distinction across presentations. Children between 2 and 9 years of age and adults participated. We predicted that even young children could judge whether a cube will sink or float, as long as variation in object density is made salient. In contrast, we expected that even older children would make mistakes when the salience of density is relatively low.

Method

Participants—Twenty-one adults (14 women and 7 men) and 58 children between 2 and 9 years of age (25 girls and 33 boys) participated in this experiment. Adults were recruited through the subject pool of introductory Psychology classes and received partial course credit for participation. Children in this and all subsequent experiments were recruited from urban and suburban middle-class day cares and elementary schools. Five additional children were tested but omitted from the analyses because they lost interest and failed to complete the task.

Materials—Ten wooden cubes were constructed according to the specifications of mass, volume, and density shown in Table 2 (adapted from Kohn, 1993): All objects were one of two densities (2.0 g/cm^3 or 0.5 g/cm^3), one of seven masses (between 30g and 503g), and one of six volumes (between 39cm^3 and 405cm^3). Neither mass nor volume alone was absolutely predictive of the cube's sinking behavior: cubes with a mass of 77g, 123g, or 197g, and cubes with a volume of 64 cm^3 , 104 cm^3 , 166 cm^3 , or 262 cm^3 could either sink or float. This full set of cubes, presented one at a time, was used for the single-presentation trials.

A subset of six cubes (from the total of ten) was combined into pairs for the pair-presentation trials, portrayed with connecting lines in Table 2. Within a pair, one cube would sink if placed in water (density = 2 g/cm^3) and the other would float (density = 0.5 g/cm^3). In addition, cubes within a pair could differ either in volume (solid lines), or they differed in mass and volume (dashed lines). Given that mass either did not correlate with density (Combination 2) or correlated negatively (Combination 4), we predicted lower accuracy on these trials than on single-presentation trials.

Cubes were hollowed out and filled with lead and wood putty until the desired mass was obtained. Care was taken to distribute mass equally throughout each cube. Once the cube was filled and closed, individual sides were painted in bright colors (each side a different color), such that cubes could not be distinguished from each other on the basis of color alone. A string of number digits, added surreptitiously to a side of the cube, made it possible for the experimenter to distinguish among the cubes.

Procedure—Participants were tested in a quiet room (either at their school or in the lab) by hypothesis-blind experimenters. The cover story involved a character named Wump who found special rocks on a far-away planet and wanted to know if the rocks would sink or float in earth water. For single-presentation trials, participants were presented with one cube at a time, each of the 10 cubes occurring twice in random order. Participants were asked to pick up the cube and report whether it would sink or float. For pair-presentation trials, participants were presented with a pair of cubes at a time, each of the six pairs occurring twice in random order, with counterbalanced left-right arrangement. For each pair, participants were asked to pick up the two cubes, and report whether one cube would sink and the other float, both cubes would sink, or both cubes would float. Participants could hold the cubes for as long as they wanted, and they were prompted to simply guess if they hesitated to respond. Randomization of trials and data collection for this and all subsequent experiments was supported by SuperLab Pro 2.0 software.

Throughout the experiment, there were no practice trials, no cube was ever placed in water, and children did not receive feedback on their performance. Therefore, learning across an experimental session was unlikely. Participants were first presented with pair-presentation trials and then with single-presentation trials, because we predicted better performance in the latter kinds of trials. Had the single-presentation trials been presented first, children might have been sensitized to density variations in the entire set, inflating performance on pair-presentation trials. Therefore, the ordering of the tasks used in Experiment 1 runs counter to our predictions, since children could potentially become attuned to mass and volume during pair-presentation trials and subsequently under-perform during single-presentation trials.

Results and Discussion

The first preliminary analysis pertained to children's performance on pair-presentation trials, when children had to decide whether one of the cubes in a pair would sink, both would sink, or both would float. On a majority of these trials (73%), participants determined that one cube would sink and the other would float. The answer option 'both sink' was chosen on 18% of trials, while the answer option 'both float' was chosen on 9% of trials. Were children affected by the particular combination of cubes (Combination 2 vs. 4; see Table 2)? To answer this question, the proportion of correct responses was collapsed across the three pairs of Combination 2 and across the two pairs of Combination 4. A repeated-measures ANCOVA, with age as a covariate, revealed no main effect or interaction of combinations, all $F_s < 0.5$, $p_s > .51$. We therefore collapsed each child's performance across the pair-presentation trials. Figure 1A displays individual children's proportion of correct responses on pair-presentation trials as a function of age. There was no significant improvement across age, $r(56) = 0.16$, $p > 0.23$, with only 48% of children (28 out of 58) performing significantly above chance (choosing the correct option on 6 or more of the 10 trials, two-tailed binomial probability $p < .05$, assuming a chance probability of 0.25).

The second preliminary analysis pertained to children's performance on single-presentation trials, when children had to decide whether a cube would sink or float. Figure 1B shows individual children's proportion of correct responses (across trials) as a function of age. There was an overall improvement across age, $r(56) = 0.50$, $p < 0.001$. As can be seen in the figure, the youngest participants (2- to 3-year-olds) performed at chance (choosing the correct option in fewer than 15 out of 20 trials; binomial probability $p > .12$, assuming a chance probability of 0.5). However, performance improved with age: Five 4- to 5-year-olds (out of 15; 33%) performed consistently above chance, and by 6 years of age, the majority of children (at least 80% per age group) performed above chance. No systematic pattern of performance was apparent when contrasting subset of cubes (e.g., the heaviest vs. lightest cubes).

To compare performance on pair-presentation trials with performance on single-presentation trials, we re-scored performance on pair-presentation pairs to gauge performance on each individual cube. This allowed us to equate chance probability across the two types of trials at 50% (children could be either correct or incorrect for each particular cube). Furthermore, we restricted our analysis to those cubes that appeared in both the pair- and the single-presentation trials (shown in the dashed box of Table 2). Figure 2 shows the mean proportion of correct performance as a function of trial type and the following age groups: 2–3 years old ($N=12$), 4–5 years old ($N=15$), 6–7 years old ($N=18$), 8–9 years old ($N=13$), and adults ($N=21$).

A 2-by-5 mixed design ANOVA was conducted, with trial type as the within-subject factor and age group as the between-subject factor. The analysis revealed a reliable linear trend of age, $F(4, 74) = 7.15$, $p < 0.01$, with participants performing better with increasing age. More importantly, the effect of trial type was statistically reliable, $F(1, 74) = 8.1$, $p < 0.01$. Children performed better on single-presentation trials ($M = 0.75$, $SD = 0.23$) than on pair-presentation trials ($M = 0.66$, $SD = 0.27$). Planned paired-sample *t*-tests revealed an effect of trial type for the three older age groups (6- to 9-year-olds and adults), paired-sample t s > 2.1 , p s < 0.05 , but not for the younger children between 2 and 5 years of age, p s $> .6$. In particular, children 6 years and older performed better on the single-presentation trials than on the pair-presentation trials, whereas children 5 years and younger failed to produce a reliable difference.

Consistent with our prediction, adults and children 6 years and older were affected by the trial-type manipulation. Participants who performed above chance were more likely to do so for single-presentation trials than for pair-presentation trials. This was true even though the exact same cubes were considered in both types of trials. Experiment 2 takes a second look at younger children's ability to pick up on difference in density, while Experiment 3 investigates whether extraneous factors of the pair-presentation, other than the targeted difference in salience, could explain children's low performance.

EXPERIMENT 2

An unexpected finding of Experiment 1 pertained to the relatively weak performance of preschool children on single-presentation trials. Previous research (e.g., Kohn, 1993) found above-chance performance for this age group, yet in our experimental set-up, children younger than 6 years of age performed at chance. It is possible that children's performance on single-presentation trials suffered from fatigue or boredom, or some other confounded factor, given that these trials always occurred last. In Experiment 2, we tested this hypothesis, presenting children between 2 and 5 years of age with single-presentation trials only (as was done in Kohn, 1993).

Method

Participants—Children between 2 and 5 years of age (9 girls, 11 boys) participated, none of whom participated in Experiment 1. The younger age group included ten 2- and 3-year-olds ($N=10$; mean age $M=3.4$ years), and the older age group included ten 4- and 5-year-olds ($N=10$; mean age $M=5.01$ years).

Materials and Procedure—Materials and procedures were identical to those used during single-presentation trials of Experiment 1. The only difference was the number of trials. There were three blocks of trials (10 trials per block), and each cube was presented once per block (resulting in a total of 30 trials).

Results and Discussion

How well could children sort cubes into sinkers vs. floaters when it was the first task they were asked to complete? Performance of the 2- to 3-year-olds did not exceed chance level, whether considering their performance during a single block of ten trials ($M_{Block\ 1} = .53$, $M_{Block\ 2} = .53$, $M_{Block\ 3} = .50$; $SDs < 0.16$), or across the a total of 30 trials ($M = .52$, $SD = 0.07$), single-sample t s < 0.9 . Only one of the ten 2- to 3-year-olds performed above chance in one block of trials (choosing the correct answer in eight out of ten trials, binominal probability $p < 0.05$). All other 2- to 3-year-olds performed at chance, whether considering only the first block of trials, or across all 30 trials.

Many 4- and 5-year-olds, on the other hand, were successful in this task. Six of the 10 4- to 5-year-olds performed above chance during the first block, and five children performed above chance across all three blocks (choosing the correct answer in at least 21 of the 30 trials, binominal probability $p < 0.05$). Figure 4 shows 4- to 5-year-olds' performance in each block of trials, separated by whether we considered all 10 cubes presented, or just the subset of cubes that were the focus of analysis in Experiment 1. Performance was above chance in both cases, whether we considered Block 1 only ($M_{All\ Cubes} = 0.72$, $M_{Subset\ of\ Cubes} = 0.77$, $SDs = 0.24$; single-sample $t(9) > 2.85$, $ps < 0.02$), or whether we considered all 30 trials ($M_{All\ Cubes} = 0.70$, $M_{Subset\ of\ Cubes} = 0.69$, $SDs < .22$, single-sample $t(9) > 2.92$, $ps < 0.02$). Importantly, performance in Block 1 was better than performance of 4- and 5-year-old children on single-presentation trials of Experiment 1 (independent-sample $t(23) = 1.79$, $p < 0.05$).

Taken together, the results show that 4- to 5-year-old children, as a group, perform successfully when presented only with single-presentation trials, replicating Kohn's (1993) finding. Apparently, 4-and 5-year-olds' performance in Experiment 1 suffered from presenting the single-presentation trials last, after the pair-presentation trials. Of course whatever factor was confounded with order in Experiment 1 is yet another non-obvious and seemingly trivial factor that determines whether children perform successfully. It is this ever-present context-sensitivity of performance that is the heart of our hypothesis.

EXPERIMENT 3

In Experiment 1, the salience manipulation was confounded – by necessity – by differences in whether objects were presented singly (single-presentation trials) or in pairs (pair-presentation trials). Making a 'sink or float' judgment about two cubes (pair-presentation trials) vs. making a 'sink or float' judgment about one cube might pose different cognitive demands on children. This difference in demand could account for the difference in performance reported in Experiment 1. Experiment 3 was designed to test for this possibility: Are 'sink or float' judgments for a pair of cubes inherently difficult?

To answer this question, children were presented only with pairs of cubes (see Table 3). For one type of pair, mass correlated positively with density, yielding *density-confounded* pairs. The heavier object in a pair was the denser one, either with volume held constant (double-dashed lines; Combination 5 in Table 1), or with an added manipulation of volume (double-solid lines; Combination 1 in Table 1). We expected competent performance to these pairs because children could perform correctly merely by paying attention to the difference in mass (while ignoring differences in density). Or they could perform correctly because the correlation between mass and density might heighten attention to both features (cf. Fisher & Tokura, 1996; Morgan, Meier, & Newport, 1987).

Conversely, in the other type of pair, mass and volume were pitted against density, yielding *density-unconfounded* pairs. Mass and volume were either negatively correlated with

density (i.e., the lighter and smaller object in a pair was always the denser one; dashed lines; Combination 4 in Table 1), or mass and volume were uncorrelated with density (density was the same despite changes in mass and volume; solid curves; Combination 3 in Table 1). For both combinations, we expected children to have difficulty correctly identifying sinkers and floaters. While the present experiment does not test children's ability to attend to density, it allows us to determine whether trials that present paired objects are inherently difficult, and thus could explain the low performance of Experiment 1.

Method

Participants—Participants were 25 4- and 5-year-old children who did not participate in the previous experiments (17 girls, 8 boys; mean age $M = 5.08$ years). This age group might be best suited to test a possible effect of cognitive demand: Children at this age are sensitive to differences in density (Experiment 2), yet their performance is more likely to suffer under the possibly higher cognitive demand of a pair-presentation context, compared to older children and adults.

Materials—Table 3 shows how the cubes were combined in Experiment 3 to create density-unconfounded pairs and density-confounded pairs. Pairs of cubes corresponded to four of the combinations shown in Table 1 (Combinations 1, 3, 4, and 5). For two of these combinations (Combinations 1 and 5; depicted in gray double-lines), mass was positively correlated with density, yielding eight density-confounded pairs. These two combinations differ in whether volume was varied (dashed double-lines, Combination 5 in Table 1) or not (solid double-lines, Combination 1 in Table 1). For the other two combinations (Combinations 3 and 4, depicted in black single lines), mass was pitted against density, yielding nine density-unconfounded pairs. These two combinations differed in whether mass and density correlated negatively (dashed lines; Combination 4 in Table 1) or not at all (solid curves; Combination 3 in Table 1).

Procedure—The procedure was identical to the pair-presentation procedure of Experiment 1 except for the different combinations of pairs that were presented. Some children were presented with Combinations 1 and 4, and other children were presented with Combinations 3 and 5. This division ensured that every child performed on density-confounded trials (Combination 3 or 4) as well as on density-unconfounded trials (Combinations 1 or 5), without creating an excessively long experimental protocol.

Results and Discussion

Preliminary item analyses revealed no difference between the first and second presentation of each unique pair (each unique pair was presented twice), $t_s < 1.6$, $p_s > 0.10$, and – after collapsing across pairs presented twice within each combination – no difference was found among different pairs within Combinations 1, 3, and 5; repeated-measure one-way ANOVA $F_s < 1.3$, $p_s > 0.34$. For the density-unconfounded pairs from Combination 4, it is noteworthy that children were much more likely to perform incorrectly when the cube pair has maximal mass difference (M_{120g} mass difference = 0.28); than when the mass difference was smaller (M_{46g} mass difference = 0.58; M_{74g} mass difference = 0.58), planned-contrast repeated-measure one-way ANOVA $F(8) = 2.1$, $p < 0.05$. This suggests that children are highly affected by the perceived difference in mass when cubes are combined into pairs. We nevertheless combined performance on pairs within Combination 4 for subsequent analyses.

Children's most common response was that one cube of the pair would sink and the other would float, when that was the correct response (Combinations 1, 4, and 5). However, children had no difficulty per se with the response options 'both float' and 'both sink'. For Combination 3, when both cubes floated, or both cubes sank, children chose these two

response options in almost half of the trials. Figure 5 shows the mean proportion of response choices ('both sink' or 'both float' vs. 'one sinks, one floats'), separated by combination. There was significant difference in proportion of 'one sinks, one floats' response options between Combination 3 (pairs for which both cubes sink or both cubes float) and Combinations 1, 4, and 5 (pairs for which one cube sinks and the other floats), planned-contrast between-group one-way ANOVA (assuming each combination as a between-subject factor $F(1,46) = 3.44, p < 0.03$).

To address the main question of the experiment, Figure 6 shows children's proportion of correct responses for density-confounded pairs and density-unconfounded pairs, either overall across trials, or for cubes that were shared across types of trials for a child. For comparison purposes, we also displayed 4- to 5-year-old's performance on the pair-presentation trials of Experiment 1 and on single-presentation trials of Experiment 2³.

Two mixed-design ANOVAs were conducted, one for the trial data, and one for shared-cubes data, with pair type as the within-subject factor (density-confounded; density-unconfounded), and group as the between-subject factor (Group 1: children presented with Combination 3 and 5; Group 2: children presented with Combination 1 and 4). There was a main effect of pair type, $F(1,24) > 10.5, ps < .01$, with children performing worse on density-unconfounded trials than on density-confounded trials, whether we considered their performance on trials ($M_{\text{Unconfounded}} = 0.46, M_{\text{Confounded}} = 0.72$) or performance on shared cubes ($M_{\text{Unconfounded}} = 0.60, M_{\text{Confounded}} = 0.80$). Neither the main effect of group nor the interaction reached significance, $F(1,24) < 1.7, ps > 0.20$.

High performance of preschoolers on the density-confounded trials rules out the possibility that the difference between trial type reported in Experiment 1 were due to differences in cognitive demand (e.g., due to pair judgments being inherently more difficult than judgments about single objects). Children easily distinguished between sinkers and floaters in a pair-condition when density and mass correlated positively. This finding contradicts the idea that children's chance performance in the pair-presentation trials of Experiment 1 was a function of high cognitive demand.

GENERAL DISCUSSION

We examined whether children's understanding of density is constrained by the distribution of mass, volume, and density in the immediate context of the task. Our hypothesis was that children would correctly predict whether an object sinks or floats when variations in density are sufficiently salient. Results of Experiments 1 and 2 support our predictions. By 5 years of age, participants performed above chance when objects were part of the set for which density was distributed saliently. Performance decreased when salience of density was reduced relative to the salience of mass and volume. Experiment 3 suggested that this difference was not merely due to differences in cognitive demand when judging paired items vs. single items.

Our findings make superfluous a discussion about what task might reflect a child's 'real' competence. If available constraints matter to successful performance, then successful performance in a single-presentation condition is not an over-estimation of a child's competence. And unsuccessful performance in a pair-presentation condition is not an under-estimation of a child's competence. Furthermore, and consistent with the well-known 'effect = structure' fallacy (e.g., Lakoff, 1990), the current findings question the need to postulate

³This comparison was appropriate, given the order effect we found between Experiment 1 and Experiment 2 for 4- and 5-year-olds' performance in the density-salient condition (see *Results* of Experiment 2).

the existence of a mental structure to explain an effect. Successful performance does not imply the existence of one kind of structure (e.g., implicit knowledge). And inaccurate performance does not imply the existence (or the lack of) a different kind of structure (e.g., explicit knowledge). Instead, differences in performance in the current task can be explained by differences in the salience of density vs. mass or volume. When density was made salient, even preschool children performed well. And when density was made less salient, performance decreased even in adults. It remains to be seen whether differences in salience of relevant dimensions could explain other context-dependent differences in performance (c.f., Diamond, 1998; Ferretti & Butterfield, 1986; Gigerenzer & Richter, 1990; Keen, 2003; Kister-Kaiser, Proffitt, & Anderson, 1985; Krist, Fieberg, & Wilkening 1993; Levin, Siegler, & Druyan, 1990; McCloskey; 1983).

Note that similarity in performance does not always imply similarity in constraints. Take for example the equivalent performance on single-presentation trials (Experiment 1) vs. density-confounded trials (Experiment 3; both $M_s = .72$). Despite similar performance, the constraints available in single-item presentations are likely to differ from the constraints available in the paired-item presentations. At the minimum, density was uncorrelated with mass in the single-item presentation, and neither mass nor volume serves as a dichotomous category marker across these trials. Conversely, in successful pair-trials, density correlated positively with mass, making available an additional distinction to affect performance. The mere difference in whether there is more than one viable stimulus dimension may change the relation between the child and the task protocol, yielding a very different basis for performance.

While the current manipulation pertained to changes in the task context, it is important to stress that constraints pertain more broadly to relations among participant, instructions, procedures, and stimuli that reduce or increase the degrees of freedom for particular response actions. Thus, constraints are not found in body, brain, or task, each working in isolation. They are discoverable only in relations between participant and task (e.g., Havas, Glenberg, & Rinck, 2007). In the current experiments, changes in the composition of stimuli changed the landscape of constraints for a child's judgments of sinking and floating. If the task were changed such that the instructions were to "throw the cubes at a target," the new task ecology would exclude previous response options while expanding the degrees of freedom for arm trajectories in throwing. And if the cubes were too heavy for the child to lift, the task ecology would change yet again.

Along the same line, if a person's knowledge (or more generally, a person's prior history) were to be changed, then a new task ecology would emerge. Recall, for example, that infants' performance in the A-not-B task, mentioned earlier, is a function (in part) of the infant's motor history (i.e., the number of reaches to one of the hiding locations prior to the crucial change in hiding location) and the infant's strength of memory traces for the hidden objects (i.e., their knowledge about where the object was hidden). Similarly, children's performance in the current experiments is a function (in part) of a child's prior history with objects. For example, a child's experience of heaviness as a downward force might heighten the salience of this dimension when it comes to judging falling or sinking behaviors (for a discussion, see Kloos & Van Orden, 2005)⁴. In other words, just as a change in task context changes task ecology, a difference in the child's prior history changes the task ecology. What kind of history would promote constraints to embody a veridical concept of density?

⁴In the current set of experiments, children did not show a bias toward focusing on mass alone. When mass was pitted against density (density-unconfounded pairs), mean performance was at chance, with a majority of children failing to base their judgment on mass alone (and thus performing below what would be predicted by chance alone). However, in different contexts, children were indeed found to focus exclusively on mass (e.g., Smith et al., 1985).

Learning about Density

How can constraints be employed to instill a sophisticated understanding of a physics concept such as density? Common teaching practices designed to replace misconceptions focus on eliciting a child's false beliefs before the child is exposed to science instruction (e.g., McDermott & Redish, 1999; Pfundt & Duit, 1991). The idea behind such practices is that false beliefs will trump formal instruction if their shortcomings are not pointed out explicitly (e.g., Kloos & Somerville, 2001). In the context of density instruction, such a procedure of initially engaging false beliefs might involve a protocol in which children are asked to relate differences in mass and volume to outcomes that are affected by density.

Results from our study suggest that such a procedure, rather than calling to mind existing beliefs, might in fact create and perpetuate them. For example, testing environments that make mass salient can lead children to rely incorrectly on mass to predict outcomes such as buoyancy (cf. Hall, 1991). Of course, once beliefs are created, they are hard to correct, not unlike a persistent priming effect (cf., Gershkoff-Stowe, Connell, & Smith, 2006) or illusory correlation effect (cf., Hamilton & Rose, 1980; Johnston & Jacobs, 2003; Lord, Ross, & Lepper, 1979). It is therefore plausible that an initial focus on mass and volume actually impedes acquiring a formal understanding of density.

A better alternative might be to avoid false beliefs altogether, namely by structuring the learning environment in such a way as to make the to-be-taught concept more salient (cf. McNeil, Uttal, Jarvin, & Sternberg, 2009; Son, Smith, & Goldstone, 2009; Uttal, Scudder, & DeLoache, 1997). For example, one could adopt a pedagogy in which density, rather than mass and volume, was most salient. The 'dots-per-box' teaching model is a point in case (Smith Maclin, Grosslight, & Davis, 1992; Smith, Maclin, Houghton, & Hennessey, 2000; Smith & Unger, 1997; Snir, Smith, & Grosslight, 1993). Students were presented with schematic representations of what an object would look like on the inside, assuming mass is expressed as number of dots, and volume is expressed as number of same-sized boxes (hence dot-per-box model). Density, therefore, is captured schematically through the visible distance among mass units within the available volume. Middle-school children were found to benefit from this visualization to understand density.

Of course, given that knowledge is always grounded in task constraints, successful performance need not necessarily lead to an abstract concept of density that will generalize to new contexts. Making density salient, such as through a box-per-dots model, allows children to perceive density directly, on the basis of attentional processes that tune in the most salient dimension. However, such direct perception might not instill an understanding of the mathematical relation between mass, volume, and density. Such lack of an abstract understanding of density might leave the learner prone to mistakes when a misleading task context makes inappropriate dimensions salient.

In order to bootstrap a more formal understanding of the concept of density, it might be necessary to combine a supportive task context with protracted weaning of students from the scaffold available in the supportive task context. This might be accomplished by providing children with diverse instances (O'Reilly & Munakata, 2000; Reeves & Weisberg, 1994) or by explicitly contrasting a supportive task context with one that leads to mistakes in performance (cf., Gentner, Loewenstein, & Thompson, 2003; Loewenstein & Gentner, 2001; see Dixon & Bangert, 2004, for a comparison between the two approaches). Both approaches might allow a student to come to embody stable and reliable biases, not unlike a young child gaining stronger memory for hidden objects in an A-not-B task. These embodied changes, while not empirically apparent, are likely to decrease the probability of making density errors in a misleading task context – the same way a stronger memory for a hidden object decreases the likelihood of searching for it at the wrong location. The effects

of task contexts can never be eliminated, however. For example, there are circumstances in which even adults commit the A-not-B error. Likewise, a sufficiently misleading task context can lead otherwise competent adults to misjudge the density of a material.

Conclusion

Our results have demonstrated that minimal changes in available constraints can influence children and adults' knowledge of density in predictable ways. These findings resolve a previous conflict between reports about children's naïve understanding of density. The resolution stems from the idea that task performance, successful or not, directly reflects the situated relations between the participant's history and the details of the experimental protocol. Consistent performance across age reflects consistently available constraints, rather than intrinsically stable beliefs or a competence. The demonstrated consequences of constraints underscore the importance of scaffolded structure in the learning environment. Our results support learning and testing approaches that include environmental support for competent performance, and only later wean performance of its supportive structure.

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A.

B.

Figure 1.

Individual children's proportion of correct performance on pair-presentation trials (A) and single-presentation trials (B). Solid lines represent chance performance ($p = .25$ for the four-choice pair-presentation trials; $p = .50$ for the two-choice single-presentation trials). Dashed lines demarcate performance that is different from chance using the binomial probability test (above chance for A: performing correctly on at least 6 out of 10 trials, above chance for B: performing correctly on at least 15 out of 20 trials; below chance for B: performing correctly on less than 5 out of 20 trials).

Figure 2.

Mean proportion of correct judgments in Experiment 1 for cubes that were presented as part of a pair (pair-presentation trials) or alone (single-presentation trials), separated by age group. Chance performance is 0.5. Error bars represent standard errors, and asterisks represent reliable differences between trial types (pair presentation vs. single presentation).

A **B** **Figure 3.**

Individual children's proportion of correct performance on pair-presentation trials (A) and single presentation trials (B). Solid lines represent chance performance ($p = .25$ for the four-choice pair-presentation trials; $p = .50$ for the two-choice single-presentation trials). Dashed lines demarcate performance that is different from chance using the binomial probability test (above chance for A: performing correctly on at least six out of 10 trials; above chance for B: performing correctly on at least 15 out of 20 trials; below chance for B: performing correctly on less than five out of 20 trials).

Figure 4.

Mean proportion of correct judgments of 4- to 5-year-olds in Experiment 2 for single cubes (single-presentation condition), separated by session. Means displayed were computed both across all cubes and across the subset of cubes that were entered into the analysis in Experiment 1. Chance performance is 0.5. Error bars represent standard errors.

Figure 5.
Mean relative frequency of choosing answer options 'one sinks, one floats' vs. 'both float' or 'both sink', separated by combination.

Figure 6.

Mean proportion of correct judgments of 4- to 5-year-olds in Experiment 3, separated by whether cubes were part of a density-unconfounded pair or a density-confounded pair (repeated-measure design). Data represent performance across pairs of a certain type or for cubes shared across the pairs in a particular combination. Corresponding means from Experiment 1 (pair-presentation trials) and Experiment 2 (single-presentation trials) are displayed for comparison purposes. Error bars represent standard errors.

Table 1

Combination of Object Pairs and Predicted Density Judgments.

Combination	Type of Pairs	Condition Label	Correlation	Predicted Density Judgment
1.		Density Confounded	Mass-Density: $r = +$ Volume-Density: $r = 0$ Mass-Volume: $r = 0$	Correct
2.		Pair-Presentation	Mass-Density: $r = 0$ Volume-Density: $r = -$ Mass-Volume: $r = 0$	Incorrect
3.		Density-Unconfounded	Mass-Density: $r = 0$ Volume-Density: $r = 0$ Mass-Volume: $r = -$	Incorrect
4.		Pair-Presentation*	Mass-Density: $r = -$ Volume-Density: $r = -$ Mass-Volume: $r = -$	Incorrect
5.		Density Confounded	Mass-Density: $r = +$ Volume-Density: $r = -$ Mass-Volume: $r = -$	Correct

Note. Pairs of cubes differ in volume (shown as different sizes), mass (the heavier of the two objects is underlined), and/or density (the denser of the two objects has a darker outline). Combination 4 was used in Experiment 1 (as part of the pair-presentation trials) and in Experiment 3 (as part of the density-unconfounded pairs).

Table 2

Masses, Volumes, and Densities of Objects used in Experiments 1–3

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

Note. Values displayed on cubes reflect their volume (in cm³). The lines connecting cubes show how cubes were combined into pairs for the pair-presentation trials of Experiment 1, with density correlating either with volume alone (solid line; Combination 3 in Table 1), or with both mass and volume (dashed line). The dashed box contains the cubes that were considered for the results. Cubes inside the dashed line were used in both conditions.

Table 3

Pairs of Cubes used in Experiment 3

Note. In density-confounded pairs (gray lines), mass and density correlate positively, either with changes in volume (dashed double-lines, Combination 5 in Table 1) or with volume fixed (solid double-lines, Combination 1 in Table 1). In density-unconfounded pairs (black lines), mass and density correlated either negatively (dashed lines; Combination 4 in Table 1) or not at all (solid curves; Combination 3 in Table 1). Children were exposed to one of the two density-confounded combinations and one of the two density-unconfounded combinations.