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ScienceDirect
Cognition 103 (2007) 227–252
COGNITION
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Interlinking physical beliefs: Children's bias towards logical congruence ☆,☆☆

Heidi Kloos *

Department of Psychology, University of Cincinnati, Cincinnati, OH 45221-0376, USA

Received 13 June 2005; revised 20 January 2006; accepted 20 March 2006

Abstract

Young children's naïve beliefs about physics are commonly studied as isolated pieces of knowledge. The current paper takes a different approach. It asks whether preschoolers interlink individual beliefs into larger configurations or Gestalts. Such Gestalts bring together knowledge such as how an object's mass relates to its sinking speed, how an object's volume relates to its sinking speed, and how mass and volume are correlated. The particular form of organization explored here is referred to as *logical congruence*, the logical correspondence in directions among three physical relations. Are children's guesses about one physical relation congruent with their beliefs about the other two relations? And can they learn a congruent set of relations more readily than an incongruent set? Two different physical domains were explored, one in which children commonly hold pre-existing beliefs, and one in which they are likely to lack such beliefs. The results in both domains show a strong bias towards congruent knowledge configurations in young children. These findings may explain children's difficulties learning inherently incongruous concepts such as density.

☆ This manuscript was accepted under the editorship of Jacques Mehler.
☆☆ This paper is based, in part, on a doctoral dissertation submitted by the author to Arizona State University, Tempe AZ. The author thanks Susan Somerville, Eric Amazeen, Clark Presson, Roger Millsap, Vladimir Sloutsky, and Guy Van Orden for their help on various parts of this paper. Furthermore, the author thanks Kelly Abraham, Nicole Bray, Lisa Holmes, and Jamae Marcinko for their help with data collection.
* Tel.: +1 513 556 5525.
E-mail address: heidi.kloos@uc.edu

0010-0277/$ - see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.cognition.2006.03.005

Keywords: Preschoolers; Naïve physics; Density; Learning; Gestalt

1. Introduction

Young children hold many naïve and incorrect beliefs about the physics of the world around them. They believe, for example, that a block should balance at its geometric middle (Karmiloff-Smith & Inhelder, 1975), that the path of ball rolling out of the spiraled tube should be curved (Kister-Kaiser, McCloskey, & Proffitt, 1986), that separate parts of the same object should move at the same speed (Levin, Siegler, & Druyan, 1990), that heavy objects should be denser than light objects (Smith, Carey, & Wiser, 1985), or that large objects should sink faster than small objects (Kloos & Somerville, 2001). While such beliefs are well documented, they are generally studied as isolated pieces of knowledge. This is to say, children's mistaken beliefs are often attributed to specific difficulties with an isolated physical relation.

The current research takes a different approach. It asks whether performance results from a congruent configuration among beliefs rather than from isolated concepts. In other words, it asks whether young children go beyond isolated beliefs and interlink them into meaningful Gestalts, that is, into higher order structures that are different from the sum of their parts. While such a possibility has been realized for young children's categorization (e.g., Keil, 1989; Barrett, Abdi, Murphy, & Gallagher, 1993) and even for their knowledge about heritance (Springer, 1995), it has not been explored with regard to their knowledge about physical regularities.

The starting point is children's mistaken beliefs about how the mass and volume of an object relate to the object's density. Young children's mistakes in this domain are well documented, but lack a comprehensive explanation, as shown below.

1.1. Mass, volume, and density

The density of an object equals the units of its mass divided by the units of its volume. Relative density determines salient aspects of an object such as its buoyancy or the rate at which it will sink through a fluid. Children's understanding of density can be tested by asking whether a particular object will sink or float (e.g., Inhelder & Piaget, 1958; Kohn, 1993), which object will sink fastest in a race (e.g., Hewson & Hewson, 1983; Penner & Klahr, 1996), or which object is made of 'the heaviest kind of stuff' (e.g., Smith et al., 1985). To perform correctly in such tasks, children must take into account both mass and volume. Yet children at preschool age (and even older) make a characteristic mistake. They often ignore differences in volume, picking the heavier of two objects as the denser object. While this bias can yield correct predictions, as when volume is held constant, it is incorrect when the heavier object is also the much larger object. In the latter case, it is the lighter object that will sink fastest.

A widely accepted explanation for this mistake is that preschoolers have an undifferentiated concept of mass and density (Carey, 1991): children do not understand that mass and density are separate features of objects. They simply equate the two features, and as a result do not understand that volume matters for determining an object's density. According to this explanation, children come to understand the relation between mass, volume, and density through experiences in which mass and density predict conflicting outcomes, and hence have to be differentiated.

While intuitive, this explanation does not account for two important findings. First, an undifferentiated concept of "mass–density" is contradicted by the finding that preschoolers can sometimes differentiate objects based on relative density (Kohn, 1993). Participants were asked to predict whether a set of objects would sink or float in water. Children between 4 and 5 years of age performed above chance when objects had extreme densities, those most different from the density of water. The objects were constructed in such a way that children could not rely on mass alone. And children were not given any prior experience with the particular objects or feedback during testing. Thus they tuned into differences in densities spontaneously, without first having to overcome an undifferentiated mass–density concept.

Second, an undifferentiated mass–density concept by itself cannot explain children's performance when objects differ solely in volume, not in mass. It predicts that children ignore an object's volume and focus on mass alone to determine relative density. Therefore, children should perform at chance when mass is held constant. Yet the findings suggest otherwise: when volume is the only varying dimension, young children hold strong beliefs about how differences in volume relate to differences in density (e.g., Inhelder & Piaget, 1958; Hewson & Hewson, 1983; Penner & Klahr, 1996; Halfort, Wilson, & Phillips, 1998; Kloos & Somerville, 2001). Specifically, they believe that large objects are denser (sink faster in water) than small objects. In other words, they ignore the mass of objects and rely instead only on differences in volume.

How can these findings be explained? The hypothesis tested here is that children inevitably interlink knowledge about mass, volume, and density (or sinking speed). More specifically, children interlink beliefs about (1) how mass affects density and (2) how volume affects density according to their overarching belief (3) that mass and volume correlate. As explained in the next section, the correlation between mass and volume often conflicts with how mass and volume actually affect density. Children may be sensitive to this conflict and express incorrect beliefs about density as a consequence.

1.2. Logical congruence

What is the potential mismatch among mass and volume, the effect of mass on density, and the effect of volume on density? To explain, the concept of *logical congruence* is introduced. This concept was applied originally to adults' beliefs about social relations (Heider, 1958; Kun, 1992). And even though the focus of the current paper is not on social relations, they are described here in some detail to convey the idea behind the concept of congruence. The social relations used by Heider referred to (1) one's attitude towards a person (e.g., Mary's attitude towards Victor), (2) one's attitude towards a topic matter (e.g., Mary's attitude towards smoking), and (3) the other person's attitude towards the same topic matter (e.g., Victor's attitude towards smoking). Of importance here is that each of these relations has a valence: the relation can either be positive (e.g., Mary likes Viktor) or negative (e.g., Mary dislikes Viktor). Depending on the valence of the relation, eight different combinations of three relations are possible (see Table 1): one set in which all three relations are positive (Set 1), three sets in which two relations are negative, while one is positive (Sets 2–4), three sets in which two relations are positive, while one is negative (Sets 5–7), and finally, one set in which all three relations are negative (Set 8).

While each combination of relations can be envisioned, the sets differ in whether they are internally congruent vs. internally incongruent, or in other words, whether the individual relations taken together are in conflict with each other. For example, while Set 1 is congruent (e.g., Mary likes Viktor, Mary likes smoking, and Viktor likes smoking), Set 5 is incongruent (e.g., Mary likes Viktor, Mary likes smoking, but Viktor dislikes smoking). In the latter example, there is a conflict between how Mary feels about smoking vs. how Victor feels about smoking, given that Mary likes Victor. As a consequence, adults will most likely change one of their attitudes.

Importantly, congruence does not pertain to the valence of a single relation or to the valences of individual pairs of relations. Instead, it is based on the way three relations combine. Note that a set of three relations is congruent when it includes an even number of negative relations (zero or two). And it is incongruent if it includes an odd number of negative relations (one or three). This meta-heuristic is useful to keep track of congruence, but it is not adults or children who are affected by congruence.

In what follows, the concept of congruence is applied to relations among physical dimensions. The three relations of interest pertain to (1) the correlation between mass and volume, (2) the effect of mass on sinking speed (when volume is held constant), and (3) the effect of volume on sinking speed (when mass is held constant). For simplicity, they will be referred to as the mass\volume, the mass\sinking speed, and the volume\sinking-speed relations, respectively. Similar to the valance of social attitudes, these physical relations have a direction. For example, the relation between

Table 1
Congruent and incongruent sets of relations

Relation	Congruent sets				Incongruent sets			
	1	2	3	4	5	6	7	8
$M \leftrightarrow V$	+	+	–	–	+	+	–	–
$M \leftrightarrow S$	+	–	+	–	+	–	+	–
$V \leftrightarrow S$	+	–	–	+	–	+	+	–

Note. The relations $M \leftrightarrow V$, $M \leftrightarrow S$, and $V \leftrightarrow S$, stand for social relations (M, Mary; V, Victor; S, Smoking) or physical relations (M, Mass; V, Volume; S, Sinking speed). The valence or direction of an individual relation can be positive (+) or negative (–). The numbers 1 to 8 refer to the possible sets of relations.

mass and sinking speed is positive (heavy objects sink faster than light objects when volume is held constant), and the relation between volume and sinking speed is negative (large objects sink more slowly than small objects when mass is held constant).

In principle, each combination of relations can be envisioned, as shown in Table 1. Take Set 8, for example: preschoolers could be taught a negative mass\volume correlation (Kloos & Amazeen, in press), they could believe incorrectly that mass is negatively related to sinking speed (Kloos & Van Orden, 2005), and they could learn that volume is negatively related to sinking speed (Kloos & Somerville, 2001). However, as in the case of social relations, not all of these sets are logically congruent. Specifically, a set of relations is congruent when it includes an even number of negative relations, and it is incongruent when it includes an odd number of negative relations.

The relations shown in Sets 1 and 5 are important for the current purposes. Set 5 contains the physically plausible relations among mass, volume, and sinking speed: the correct relation between mass and sinking speed is positive (assuming volume is held constant); the correct relation between volume and sinking speed is negative (assuming mass is held constant); and for objects of the same material, mass and volume correlate positively. Yet this set of relations (and therefore the concept of density instantiated in the real world) is incongruent. Indeed, children struggle most with one relation in this set, the negative effect of volume on sinking speed.

As stated above, children believe incorrectly that large objects sink faster than small objects, all else equal. Thus, children's naïve physics of mass, volume, and sinking speed is well represented by Set 1: children assume that mass and volume correlate positively (Hauer, Mounoud, & Mayer, 1981) and that both mass and volume are positively related to sinking speed. The question is whether children's tendency to hold onto this congruent set of beliefs (Set 1), rather than to the correct but incongruent set of beliefs (Set 5), has something to do with congruence. Are children naturally biased to sustain congruent sets of beliefs and thereby sometimes express incorrect beliefs?

1.3. Overview of experiments

Three experiments were conducted to test whether young children tend to adopt congruent sets of beliefs. The age group of particular interest was preschool (children between 4 and 5 years of age). Children in this age group hold strong beliefs about physical relations (e.g., Karmiloff-Smith & Inhelder, 1975), yet have not received systematic instruction about physical concepts. Any form of organized knowledge is therefore spontaneous and might reflect a basic Gestalt principle of reasoning.

Experiments 1 and 2 pertain to the features mass, volume, and sinking speed and hence to the relations mass\volume, mass\sinking speed, and volume\sinking speed. Experiment 1 examines whether children make congruent guesses about an unseen sinking-speed relation. More specifically, children were taught about two relations (e.g., mass\volume and mass\sinking speed) and asked to guess the direction of the third relation (e.g., volume\sinking speed). If children are biased towards congruence, the guessed direction should depend on the direction of the learned relations. For example, children presented with a positive and a negative relation should guess a negative relation, independently of whether the guessed relation pertains to mass/sinking speed or volume/sinking speed.

In Experiment 2, children were presented with all three relations (i.e., mass\volume, mass\sinking speed, and volume\sinking speed), the only difference being the direction of the mass\volume correlation. That is to say, children were presented with a positive mass\sinking-speed relation, a negative volume\sinking-speed relation, and either a positive or a negative mass\volume correlation. When the mass\volume correlation was positive, the set of three relations was incongruent (cf. Set 5 in Table 1), and when the mass\volume correlation was negative the set of three relations was congruent (cf. Set 3 in Table 1). If children are biased towards congruence, they should learn the sinking-speed relations best in the latter case where the relations are congruent amongst each other. Thus, Experiment 2 examines whether children learn two sinking-speed relations differently depending on whether the relations are embedded in a congruent or an incongruent triad of relations.

Finally, Experiment 3 tested the generality of children's bias towards congruence with a new set of features about which children are unlikely to have a priori beliefs. The sizes of two arbitrarily linked shapes, a rectangular base and a supported disc, replaced mass and volume. And the size of the shadow cast by the disc replaced sinking speed. Apart from these differences in feature content, the methodology and logical design of Experiment 2 were conceptually replicated: children were presented with congruent or incongruent sets of relations. If children are biased towards congruence, their ability to learn the relations should differ as a function of overall congruence.

2. Experiment 1

Preschool children participated in one of four conditions illustrated in Table 2. The conditions differed in what relations were presented to children during training and what relations needed to be guessed. In condition 1, children were presented with a positive mass\volume correlation and a positive mass\sinking-speed relation. They guessed the volume\sinking-speed relation. In condition 2, children were presented

Table 2
Design of Experiment 1

Relation	Conditions			
	1	2	3	4
Mass\volume	+	+	−	−
Mass\sinking-speed	+	? (+)	+	? (+)
Volume\sinking-speed	? (−)	−	? (−)	−
	Incongruent sets		Congruent sets	

Note. The conditions differed in the kind of relations presented to children, a relation being either positive (+) or negative (−). Children had to guess the relation marked with '?'. The physically correct direction of the to-be-guessed relation is given in parentheses (either positive or negative). The physically correct relation is congruent in conditions 3 and 4 and incongruent in conditions 1 and 2.

with a positive mass\volume correlation and a negative volume\sinking-speed relation. They guessed the mass\sinking-speed relation. In condition 3, children were presented with a negative mass\volume correlation and a positive mass\sinking-speed relation. They guessed the volume\sinking-speed relation. And in condition 4, children were presented with a negative mass\volume correlation and a negative volume\sinking-speed relation. They guessed the mass\sinking-speed relation.

Table 2 shows the correct direction of a guessed relation in parentheses. If children would make correct guesses, they would guess a positive relation between mass and sinking speed (heavy object sink faster than light objects), and they would guess a negative relation between volume and sinking speed (small objects sink faster than large objects). Such correct guesses yield an incongruent set of relations in conditions 1 and 2 (there would be an odd number of negative relations), and they yield a congruent set in conditions 3 and 4 (there would be an even number of negative relations). Therefore, if children are biased towards congruence, they should be more likely to guess the correct relation in conditions 3 and 4 than in conditions 1 and 2, irrespective of whether they guess the mass\sinking-speed or the volume\sinking-speed relation.

2.1. Method

2.1.1. Participants

For this and all other experiments reported here, preschoolers were recruited from suburban day care centers serving predominantly white, middle-class families. The sample in this experiment consisted of 14 girls and 17 boys, who were randomly assigned to one of the four conditions (see Table 2; $n = 8$ per cell). The mean age in years was 5.2 ($SD = 0.43$), 5.0 ($SD = 0.48$), 5.2 ($SD = 0.40$), and 5.0 ($SD = 0.52$) for children in conditions 1, 2, 3, and 4, respectively.

2.1.2. Materials

The sinking objects were black PVC pipes (diameter = 5 cm) closed with lids on either end. Each cylinder had a piece of lead inside, which was held in place with Balsa wood. The center of mass coincided with the geometric center of the cylinder, so the objects would sink in a uniform pattern. A cylinder weighed 130, 200, 300, or 450 g, and was 6, 9, 13, or 19 cm high. To provide children with a visual cue to the heaviness of each cylinder, horizontal lines (each 4 cm long) were drawn onto white contact paper and glued on the lower part of the cylinder. The heavier the cylinder, the more lines were drawn (2 lines for 130 g, 3 lines for 200 g, 4 lines for 300 g, and 6 lines for 450 g)[1].

Three sets of four cylinders were created that differed in how mass and volume correlated. For four cylinders, mass and volume correlated positively (the heavier

[1] The distance between the bottom and top line on a cylinder was 4 cm and did not differ across cylinders of different masses. Instead, the distance between adjacent lines varied. Depicting mass in this way avoided the potential confound with extension (i.e., height of lines) that could otherwise have put children at an advantage who were presented with a positive mass\volume correlation.

cylinder was also the larger one). This set was used to convey the positive mass\volume correlation. For another four cylinders, mass and volume correlated negatively (the heavier cylinder was also the smaller one). This set was used to convey the negative mass\volume correlation. And for the last set of four cylinders, mass and volume did not correlate. Two cylinders weighted 200 g, one being 9 cm tall and the other being 13 cm tall; and the other two cylinders weighted 300 g, again one being 9 cm tall and the other being 13 cm tall. The last set of objects was used to demonstrate the sinking-speed relations.

In addition to real objects, schematic drawings of different masses and volumes were used. Each mass was represented as horizontal lines (2, 3, 5, 8, or 12 lines; length of a line = 2 cm) drawn onto a white square (3.5 by 3.5 cm). And each volume was represented as a dark rectangle (3.5 cm wide) of a particular height (3.3, 4.1, 5.1, 6.4, or 8 cm). Schematics of 'whole objects' were created by gluing a particular 'mass' picture onto a particular 'volume' picture.

Two sets of whole-object pictures were created, one set illustrating a positive mass\volume correlation, and the other set illustrating a negative mass\volume correlation. The two sets of whole-object pictures were distributed symmetrically along the diagonal of a 30×45 cm poster to illustrate the mass\volume correlation. The correlation (positive or negative) displayed on the poster was not perfect. In particular, there were at least two levels of mass for each level of volume, and there were at least two levels of volume for each level of mass. This conveyed to children that the overall correlation in the set of cylinders was not true for every pair of cylinders.

A tall water tank (30 cm deep, 60 cm wide, and 90 cm tall) was used to demonstrate the sinking behavior of the cylinders. The tank had a vertical dividing wall to ensure that two cylinders could sink next to each other without interference.

2.1.3. Procedure

The cover story involved a submarine man (i.e., a 6 cm tall Lego man) who builds toy submarines and thinks he knows which submarine will sink fastest in water. Children's task was to first learn about what makes submarines sink really fast, and then play against the submarine man in designing a faster submarine.

Prior to training and testing, children participated in a familiarization phase in which they were shown a cylinder of medium volume and medium mass. The cylinder was said to be a toy submarine with several weights inside. A metal disc (diameter = 3.5 cm, height = 0.3 cm) was used to illustrate the shape of the weights inside the submarine. Children were told that the horizontal lines drawn on the bottom part of a submarine show its number of weights: each line represents one weight. Children readily accepted this representation of mass and frequently talked about the number of weights to convey differences in mass between cylinders. The example cylinder was then released into the water tank to demonstrate its sinking speed.

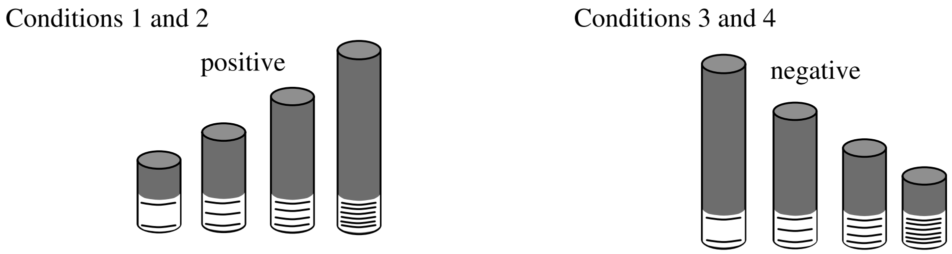
The ensuing procedure involved (1) teaching children the mass\volume correlation, (2) demonstrating a sinking-speed relation, and (3) testing children's beliefs about the two sinking-speed relations. These three steps are shown schematically in Table 3 and are described in detail below.

2.1.3.1. Teaching the mass\volume correlation. Following familiarization, children were shown the poster with the submarine pictures. The correlation between mass and volume (either positive or negative) was described verbally. Specifically, children were told: “Before we can find out about how the submarines sink, let’s look at some submarines. Some are tall and some are short, and some are heavy and some are light. Look, the ones that are smallest are often lightest (heaviest). As the submarines

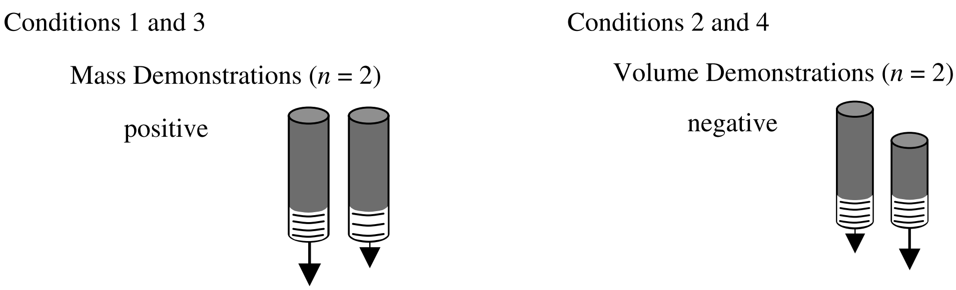
Table 3
Schematic representation of the procedure used in Experiment 1

Procedural steps

1. Teaching the mass\volume correlation



2. Demonstrating one sinking-speed relation



3. Testing final beliefs about the sinking-speed relations: (same for all conditions)

Note. Steps 1 and 2 were conducted with cylinders, while Step 3 was conducted with pictures. The number of lines signifies a particular mass. In Step 2, the longer arrow signifies the faster sinking cylinder. In Step 3, the child had to choose one of the two test options to design a submarine that would sink faster than the standard.

get taller, they often get heavier (lighter). The ones that are tallest are often heaviest (lightest). That is how the submarine man builds the submarines''.

Next, children were presented with the four cylinders that comprised the mass\volume correlation (see step 1 of Table 3). The cylinders were placed in a random order in front of the child, and the child was encouraged to explore them. The next task was to order the cylinders according to one feature (e.g., mass), and then according to the other feature (e.g., volume; in counterbalanced order). In the rare event in which a child produced an incorrect ordering, the experimenter corrected it, placed the cylinders in a new random order, and asked the child to order the cylinders again. No child needed more than one prompt. Each child produced two correct orderings for each feature.

To assess whether children could learn the mass\volume correlation, a partial screen was used (30×45 cm) that had an opening on its lower part (45 cm long, 5 cm high). When the cylinders were placed behind the screen in an upright position, the horizontal lines depicting mass were visible through the opening, but not the height of the cylinders. When cylinders were laid down flat and placed through the opening, the relative height of the cylinders was visible, but not the number of lines. Placing the cylinders behind this partial screen tested whether children could determine the relative mass of a cylinder given its volume, or vice versa whether children could determine the relative volume of a cylinder given its mass.

Cylinders were aligned in random order behind the right side of the screen (from the child's perspective). Children were asked to order the cylinders according to the feature obscured by the screen. They were instructed, for example when only the lines of the cylinders were visible, ''Now you can only see how heavy the submarines are, and you cannot see how tall they are. But do you remember from before? The taller submarines were often heavy (light). Which one of these submarines is the tallest one? Which one comes next?'' A child's choice was placed on the left side of the screen followed by the next choice and so on. The cylinders were kept behind the screen until the ordering was completed. Then the screen was removed and children were encouraged to look at the cylinders briefly before they were placed behind the screen again. This time, the previously visible feature was now occluded, and the previously occluded feature was now visible. Again, children were asked to order the cylinders according to the occluded feature. The order of occlusion was counterbalanced across children (i.e., occluding mass first then volume, or occluding volume first then mass).

2.1.3.2. Demonstrating one sinking-speed relation. Demonstrations consisted of 'submarine races' of two cylinders. Children in conditions 1 and 3 were presented with *mass demonstrations*: the two racing submarines differed only in mass, while volume was held constant. And children in conditions 2 and 4 were presented with *volume demonstrations*: the two racing submarines differed only in volume, while mass was held constant. Step 2 in Table 3 shows an example of the racing submarines in each type of demonstration. When cylinders differed only in mass, the heavier object sank fastest, and when cylinders differed only in volume, the smaller object sank fastest. Each child saw two submarine races.

During a submarine race, children were presented with two cylinders and two pictures. During mass demonstrations, the two pictures depicted two different levels of mass (i.e., two squares, one with three and one with eight lines), and during volume demonstrations, the two pictures depicted two different levels of volume (i.e., two rectangles; 4.1 and 6.4 cm high). Children were told: "These pictures will help us remember what makes a submarine sink faster in water". The first task was to determine how the two cylinders differed. Special care was taken to explain to children that one feature (depending on condition, either mass or volume) did not differ within a pair. Next, children had to match each picture with the corresponding cylinder (e.g., the taller rectangle had to be matched with the taller cylinder). The experimenter then dropped the pair of cylinders into the water tank. After the race, children were asked to point to the winner in the tank and to the picture matching it. None of the children had difficulties with these subtasks. They acknowledged the outcome for each race and could understand the correspondence between real objects and pictures.

2.1.3.3. Testing final beliefs. To test children's beliefs of the individual sinking-speed relations, children had to design a submarine that would sink faster than a submarine designed by the submarine man. Two types of trials were used, four *mass trials* and four *volume trials*, presented in random order to all of the children. The mass trials assessed children's belief about the mass\sinking-speed relation, and the volume trials assessed children's beliefs about the volume\sinking-speed relation. Note that for conditions 1 and 3, mass trials tested children's ability to learn from the demonstrations, while volume trials tested their guesses about the unseen relation. And for conditions 2 and 4, mass trials tested children's guesses about the unseen relation, while volume trials tested their ability to learn from demonstrations (cf. Table 2).

In each trial, children were given a set of pictures (see step 3 of Table 3 for an example of a mass trial and an example of a volume trial). One picture contained both mass and volume information (a white square with lines glued onto a black rectangle) and represented the submarine designed by the submarine man (i.e., the standard). Two other pictures represented a child's choice to design the faster submarine (i.e., test options). During mass trials, the child could choose between two masses (i.e., two white squares, one with fewer lines and the other with more lines than the standard). And during volume trials, the child could choose between two volumes (i.e., two rectangles, one taller and one shorter than the standard)[2].

Children's belief about the mass\volume correlation was re-tested at the end of the experimental session. Cylinders that comprised the mass\volume correlation were placed behind the partial screen without presenting them to children in full view. For half of the children, the screen occluded volume, and for the other children, the screen occluded mass. Children were asked to order the cylinders according to the occluded feature. They were told: "Remember from before how we played this game?

[2] To make the task of designing a submarine credible, a test trial included an additional picture, not shown in Table 3, which children needed to complete their submarine. This picture represented a volume during mass trials, identical to the volume of the standard; and it represented a mass during volume trials, identical to the mass of the standard.

You cannot see how tall (heavy) the submarines are; you can only see how heavy (tall) they are. But do you remember which one was the tallest (heaviest)? Which one comes next?" The specific correlation was not pointed out to them. Children's choice was placed on the left side of the screen, followed by their next choice, and so on. The cylinders were kept behind the screen until the ordering was completed.

2.2. Results and discussion

All children successfully learned the mass\volume correlation. Children correctly ordered the four cylinders behind the partial screen in both the initial testing phase and the re-testing at the end of the experiment. In other words, they correctly determined the magnitude of the occluded feature on the basis of the visible feature. This is not surprising given the extensive training with pictures, cylinders, and verbal descriptions of the correlation. In fact, pilot testing revealed that children could learn the positive or negative mass\volume correlation even after mere exposure to the cylinders, without being given any verbal description of the correlation (see also Kloos & Amazeen, in press).

2.2.1. Beliefs about the demonstrated relation

A first analysis pertained to whether children could learn the sinking-speed relation presented to them during the demonstrations. In conditions 1 and 3, this analysis pertained to children's performance in mass trials, and in conditions 2 and 4, this analysis pertained to children's performance in volume trials. With few exceptions, children performed correctly during these trials. Specifically, in conditions 1 and 3, only one child (out of 16) performed incorrectly in mass trials (this child always chose the lighter mass option). And in conditions 2 and 4, only four children (also out of 16) performed incorrectly in volume trials (three children always chose the larger volume option, and one child chose the larger option in half of the trials).

2.2.2. Beliefs about the unseen relation

The second analysis pertains to children's guesses about the sinking-speed relation that was not demonstrated to them. In conditions 1 and 3, this analysis pertained to children's performance in volume trials, and in conditions 2 and 4, this analysis pertained to children's performance in mass trials. Fig. 1 shows the mean proportion of correct guesses as a function of condition. Only those children are included here who performed correctly on trials that tested their belief about the demonstrated relation ($n = 27$)[3]. As can be seen from the figure, children performed largely correct when the physically correct relation was congruent with the two learned relations

[3] Four of the five excluded children were affected by congruence. Three of them always picked the heavier mass option (i.e., positive mass\sinking speed) and the larger volume option (i.e., positive volume\sinking speed) after being taught a positive mass\volume correlation (cf., Set 1 in Table 1), and one child picked the lighter mass option (i.e., negative mass\sinking speed) and the larger volume option (i.e., positive volume\sinking speed) after being taught a negative mass\volume correlation (cf., Set 4 in Table 1).

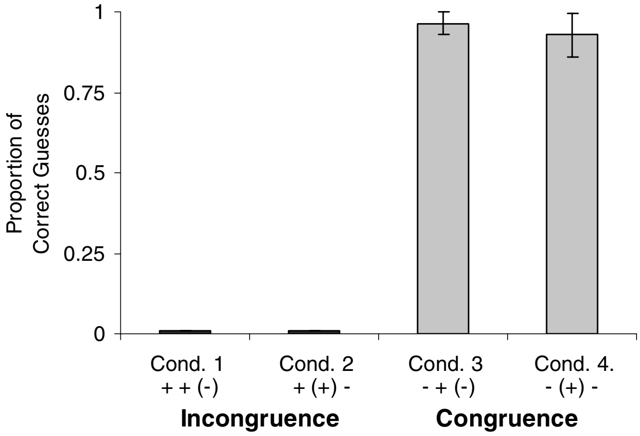


Fig. 1. Proportion of correct guesses as a function of condition in Experiment 1. The directions of the three relations are shown underneath each condition, which the first direction referring to the mass\volume correlation, the second direction referring to the mass\sinking-speed relation, and the third direction referring to the volume\sinking-speed relation. The direction in parenthesis refers to the correct direction of the to-be-guessed relation. If children would make correct guesses, the resulting set of beliefs would be incongruent for conditions 1 and 2, and congruent for conditions 3 and 4.

($M = 0.95$, $SE = 0.04$). Conversely, none of the children performed correctly when the physically correct relation was incongruent within the set ($M = 0$).

Note that children in the two Incongruence conditions (conditions 1 and 2) made incorrect guesses rather than performing at chance (assumed chance probability: $p = 0.5$). In condition 1, children consistently picked the larger volume option (i.e., they guessed a positive volume\sinking-speed relation), and in condition 2, children consistently picked the lighter mass option (i.e., they guessed a negative mass\sinking-speed relation). These guesses – while physically incorrect – yielded congruent sets of beliefs (condition 1: three positive relations; condition 2: one positive and two negative relations).

The pattern of findings cannot be due to isolated difficulties with one of the sinking-speed relations, as children readily learned the sinking-speed relation presented to them during demonstrations. Nor can it be explained by a match between only two relations, such as a simple match between the mass\sinking-speed and the volume\sinking-speed relation. Instead, the results show that children took into account all three relations. Their guesses about the unseen sinking-speed relation were congruent with their two beliefs about the mass\volume correlation and the observed sinking-speed relation.

3. Experiment 2

A stronger demonstration of children's bias towards congruence would require children to contradict what they had observed previously. Do children favor congruence even though their observations contradict it? Experiment 2 answered this question. The procedural steps closely match those of Experiment 1, with the only difference being that children were presented with both sets of sinking demonstrations. That is, no guessing was necessary because the child saw how mass is related to sinking speed (when volume was held constant) and how volume is related to sinking speed (when mass was held constant).

As was done in Experiment 1, children were initially taught about the correlation between mass and volume. For children in the Incongruence condition, this correlation was positive, and for children in the Congruence condition, this correlation was negative (see Table 4). If children are affected by the congruence among the three relations, they should be more likely to learn the physically correct sinking-speed relations in the Congruence than in the Incongruence condition. In the Incongruence condition, children should systematically misrepresent one of the sinking-speed relations to obtain a congruent set of relations overall.

To test the robustness of the effect, the age group was expanded in the current experiment to range between 4 and 7 years of age. While previous research about knowledge organization commonly failed to find an age difference between preschoolers and elementary-school children (e.g., Barrett et al., 1993; Springer, 1995), other kinds of tasks show a rather substantial developmental gap between 5- and 7-year olds (e.g., Siegler, 1996).

3.1. Method

3.1.1. Participants

Thirty-two 4-to 7-year-olds participated (17 girls and 15 boys), none of whom had participated in Experiment 1. School-aged children were recruited from after-school programs serving working-class families from a wide range of ethnicities. Two age groups were created (4- to 5-year olds and 6- to 7-year olds), and within each age group children were placed randomly in one of the two conditions ($n = 8$ per condition). The mean ages in years were 5.3 ($SD = 0.60$) and 6.9 ($SD = 0.45$) for children in the Incongruence condition, and 5.3 ($SD = 0.54$) and 7.1 ($SD = 0.70$) for children in the Congruence condition.

Table 4
Design of Experiments 2 and 3

Experiment 2	Conditions		Experiment 3
	Incongruence	Congruence	
Mass\volume	+	–	Disc\base
Mass\sinking-speed	+	+	Disc\shadow
Volume\sinking-speed	–	–	Base\shadow

Note. The conditions differed only in the direction of the initially learned correlation (mass\volume in Experiment 2 and disc\base in Experiment 3).

3.1.2. Materials

The same materials were used as in Experiment 1.

3.1.3. Procedure

The same procedure was used as in Experiment 1 (see Table 3), with the only difference being that children were shown both sets of sinking demonstrations (mass demonstration and volume demonstration), instead of only one. For half of the children within each age group and condition, the first two races were mass demonstrations followed by two volume demonstrations, and for the other children, this order was reversed. As was found in Experiment 1, all children performed correctly in the individual sub-tasks during a demonstration race. Furthermore, children performed correctly in the ordering tasks that tested their understanding of the mass\volume correlation (when cylinders were placed behind the partial screen, either prior to the demonstrations and at the end of the testing phase).

3.2. Results and discussion

The results of interest pertain to children's performance during the four mass trials and four volume trials, when children had to design the faster submarine (see step 3 in Table 3). Fig. 2 shows the mean proportion of correct responses (i.e., choosing the heavier mass option, and choosing the smaller volume option) as a function of condition and age group. A 2 (condition: Congruence vs. Incongruence) by 2 (age group: 4- and 5- year olds vs. 6- and 7-year olds) between-subjects ANOVA revealed a significant main effect of condition, $F(1,28) = 49.7$, $p < 0.001$, with children in the Congruence condition performing better ($M = 0.90$, $SE = 0.05$) than children in the Incongruence condition ($M = 0.53$,

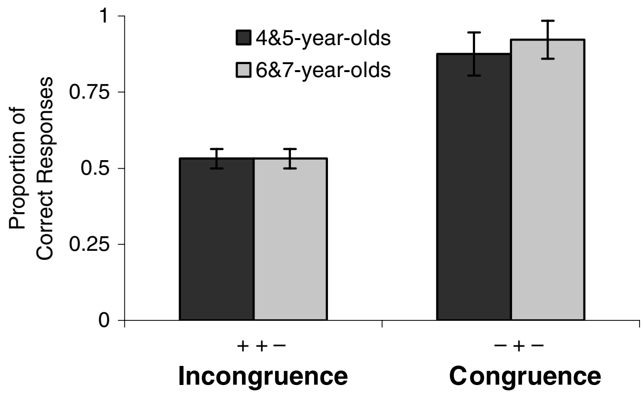


Fig. 2. Proportion of correct responses, averaged across mass and volume trials, as a function of condition and age group in Experiment 2. The directions of the three relations are shown underneath each condition, with the first direction referring to the mass\volume correlation, the second direction referring to the mass\sinking-speed relation, and the third direction referring to the volume\sinking-speed relation.

$SE = 0.02$). No effect of age was found, $p > 0.6$. These results show that children in both the younger and older age group could learn the two sinking-speed relations better when the two relations were congruent within the set than when the two relations were incongruent.

Children's mean performance in the Incongruence condition did not differ from what would be expected by chance (assumed chance probability: $p = 0.5$). However, individual children's patterns of responses indicate that children rarely performed at chance. Only three children (2 younger children and 1 older child, out of 32) performed at chance in one or both types of trials (mass trials, volume trials). All other children systematically misinterpreted one of the sinking-speed relations. About half of the children (44%; 3 younger and 4 older children) performed incorrectly on volume trials (positive volume\sinking-speed relation), while being correct on mass trials (positive mass\sinking-speed relation). And the other children (38%, 3 younger and 3 older children) performed incorrectly on mass trials (negative mass\sinking-speed relation), while being correct on volume trials (negative volume\sinking-speed relation). Both groups of children ended up with a congruent set of beliefs (see Table 1, Sets 1 and 2, respectively).

Taken together, Experiments 1 and 2 demonstrate a strong bias towards congruence among mass, volume, and sinking speed in children between 4 and 7 years of age. When presented with objects that differ in mass and volume, and tested about the effects of mass and volume on sinking speed, children were affected by how mass and volume correlated.

4. Experiment 3

The goal of Experiment 3 was to test the generality of young children's bias towards congruence with a new set of feature relations. One could argue that bias towards congruence is limited to the domain of sinking objects that differ in mass and volume, because the features mass, volume, and (sinking) speed are saliently related to each other in children's everyday environment. An object of a particular mass always has a particular volume, and it always has a particular speed when thrown, dropped, or pushed. Even infants seem to relate the size of an object to the distance it will travel when rolled down a ramp (Kotovsky & Baillargeon, 1998).

One way to decrease a relation's a priori salience is to use dimensions that are spatially separated (cf. Loewenstein & Gentner, 2001). In Experiment 3, composite objects were created by attaching two separate shapes perpendicularly to each other. One shape was a disc, and the second shape was a rectangle (also referred to as the base of the composite object). Composite objects could be placed between a screen and a light source in such a way that the disc would project a shadow onto the screen (Fig. 3). The resulting three features were (1) the diameter of the disc, (2) the length of the base, and (3) the size of the shadow projection on the screen.

The features were chosen in such a way that the resulting relations corresponded to the relations among mass, volume, and sinking speed. Disc size was positively

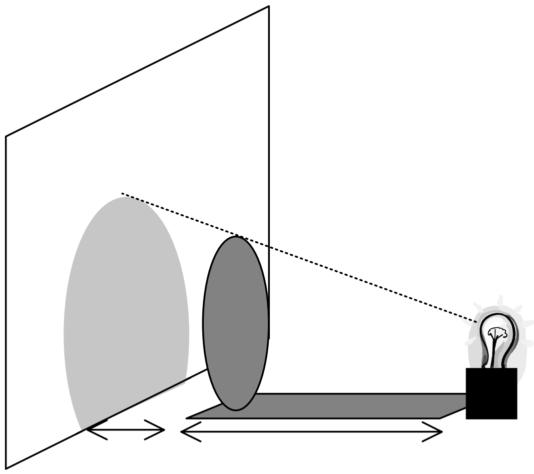


Fig. 3. Shadow projection of an object used in Experiment 3. A 3 cm fixed distance, illustrated by the short double-headed arrow, was maintained between object and screen. The length of the object's base, illustrated by the longer double-headed arrow, determined the distance between light source and disc.

related to shadow size, just like mass was positively related to sinking speed. Base length was negatively related to shadow size, just like volume was negatively related to sinking speed. And the correlation between disc and base size could be manipulated to be positive or negative, just like the correlation between mass and volume.

Design and procedure were isomorphic to that of Experiment 2, with children participating either in the Congruence or the Incongruence condition (see Table 4). Half of the children were initially taught a positive disc\base correction (Incongruence condition), and the other children were initially taught a negative disc\base correlation (Congruence condition). All children were then presented with a positive disc\shadow relation and a negative base\shadow relation. If children are biased towards congruence among the three relations, they should learn the two shadow-size relations better in the Congruence than the Incongruence condition.

4.1. Method

4.1.1. Participants

Given that no age difference was found in Experiment 1, only 4- and 5-year olds were tested in this experiment (10 girls and 6 boys). Children were placed randomly in one of the two conditions ($n = 8$ per condition), with the mean ages being 4.9 years ($SD = 0.54$) for children in the Incongruence condition and 5.2 years ($SD = 0.32$) for children in the Congruence condition.

4.1.2. Materials

The stimuli were composite objects that consisted of a wooden disc (thickness = 0.3 cm) attached perpendicularly to a rectangular base made from the same material (width = 1 cm). The diameter of the disc could be 4, 5, 6, or 7 cm, and the length of the base could be 4, 6, 9, or 12 cm. The different discs and bases were combined to create three sets of four objects, one set in which disc and base correlated positively, one set in which disc and base correlated negatively, and one set in which disc and base did not correlate. A partial screen (30 × 45 cm) with an opening along the bottom (30 cm long, 1 cm high) was used to test children's understanding of the disc\base correlation. The composite objects could be placed through the opening in such a way that one shape (either disc or base) was visible, while the other shape was occluded.

Two kinds of pictures were used, ones that were schematic representations of whole objects (with disc and base drawn in perspective), and ones that were schematic representations of a single shape (either disc or base). The disc diameter was 2, 2.5, 3.1, 3.8, or 4.6 cm and the base length was 3, 4, 5.1, 6.2, or 7.3 cm. The whole-object pictures were used to convey the correlation between disc size and base size, and were glued onto a poster board equivalent to what was done in Experiments 1 and 2 with pictures of cylinders.

To create a shadow, a white screen was used, covered by a 'roof' to block the light from the testing room. A dividing wall was attached perpendicularly to the screen so that two objects (each with its own light beam) could create shadows at the same time without interference. Fig. 3 shows how a single object was placed in relation to screen and light source. The distance between disc and screen was held constant (3 cm), and the distance between disc and light source was determined by the length of the base. The light source (one for each object) was a small flashlight attached to wheels.

4.1.3. Procedure

The procedure was analogous to the procedure of Experiment 2, the main difference being the different instructions linked to the different objects and events. A brief description of the procedure is given next.

Children were invited to play the Moon Game, a pretend game about shadow makers that are built by the moon man (i.e., the small Lego man). Children were told: "The moon man built these things to make shadows", and the shadow of one object was demonstrated. The child's task was to learn about what makes an object have a big shadow, and then to design a shadow maker that would have bigger shadows than the shadow makers of the moon man.

After familiarization, children were taught the disc\base correlation with objects, pictures, and verbal statements (analogous to step 1 of Table 3). Children's belief about this correlation was then assessed by placing the objects behind the partial screen and by asking children to order the object according to the occluded shape (either disc or base). All children produced two correct orderings for each occluded shape.

Children were then presented with two sets of shadow demonstrations (analogous to step 2 of Table 3). One set pertained to the effect of disc size on shadow size (disc demonstrations) and the other set pertained to the effect of base size on shadow size (base demonstrations). During each demonstration, two objects were used that differed only in the relevant feature (either disc diameter or base length), while the other feature was held constant. A pair of pictures accompanied the objects. When the objects differed in disc size, the accompanying pictures showed a big and a small disc, and when the objects differed in base length, the accompanying pictures showed a long and a short base. After children matched the picture with the corresponding object, each object was placed between shadow screen and light source as shown in Fig. 3. The flash lights were turned on, and children had to determine which of the two shadow makers created the larger shadow. Finally, they had to match the winning shadow maker with the corresponding picture. None of the children had difficulty with these subtasks.

Children's final beliefs about the disc\shadow and base\shadow relation were assessed next (analogous to step 3 of Table 3). In eight trials (four disc trials and four base trials), children were asked to design a shadow maker that would have a bigger shadow than the shadow maker of the moon man. During disc trials, test options consisted of two differently sized discs (one disc being smaller and the other being larger than the disc of the standard), and during base trials, test options consisted of two differently sized bases (one base being shorter and the other being longer than the base of the standard). At the end of the procedure, children's understanding of the disc\base correlation was re-assessed and revealed accurate performance.

4.2. Results and discussion

The results of interest pertain to children's performance during the four disc trials and the four base trials. An independent-sample *t*-test revealed a significant difference between the two conditions, $t(14) = 2.7$, $p < 0.03$, with better performance in the Congruence condition ($M = 0.75$, $SE = 0.08$) than in the Incongruence condition ($M = 0.51$, $SE = 0.02$). These findings demonstrate a bias towards congruence equivalent to that found in Experiment 2. Children learned the two shadow-size relations better when they were part of a congruent set than when they were part of an incongruent set. To compare the results between Experiments 2 and 3, a 2 by 2 (Experiment by Condition) between-subject ANOVA was conducted, including only the 4- and 5-year-olds of Experiment 2. The results did not yield a significant main effect of experiment or a significant interaction, $ps > 0.23$.

Children's performance in the Incongruence condition was analyzed separately for disc and base trials to determine whether children performed at chance, as the overall mean might suggest. The findings show that this was not the case. Children performed largely correct on disc trials ($M = 0.88$, $SE = 0.08$), choosing the larger disc to create the larger shadow. And they performed largely incorrect on base trials ($M = 0.16$, $SE = .06$), choosing the larger base to create the larger shadow. The resulting beliefs (positive disc\shadow belief and positive base\shadow belief) are congruent with the positive disc\base correlation taught to children in this condition (cf., Set 1 of Table 1). This suggests – as in Experiment 2 – that children were biased towards congruence even after being taught an incongruent set of relations.

5. General discussion

Three experiments investigated whether young children interlink isolated beliefs about physical regularities. Of particular interest was whether preschoolers use the organizing principle of congruence – a principle well known in the domain of adults' social relations (Heider, 1958). If children interlink their beliefs according to this principle, their beliefs about how features correlate should follow logically from each other and not be in conflict. Two different domains were examined, one in which children are likely to hold strong beliefs (Experiments 1 and 2) and one in which such strong beliefs are unlikely (Experiment 3). In each domain, children were presented with information about how features are related to each other. After that, their belief about each feature relation was tested. The results can be summarized as follows:

Young children were surprisingly unaffected by the physically correct direction of a relation. Instead, their beliefs were governed by the principle of congruence. Children could learn (or guess) the correct direction of a relation only when it was congruent within the set of three relations (Congruence condition). When the correct direction of a relation yielded an incongruent set (Incongruent condition) children made systematic mistakes to maintain a congruent set of beliefs. Such mistakes cannot be explained by children holding mistaken beliefs prior to the experimental manipulation. Although children's a priori beliefs were not assessed, children were randomly assigned to conditions, and hence, children should be equally likely to perform incorrectly. Yet in Experiment 2, for example, only 19% of children performed incorrectly in the Congruence condition, compared to 100% of children in the Incongruence condition. Note also that congruence was not provided by the experimenter. For example, in Experiment 2, the correlation between mass and volume was never presented during the submarine races. In fact, children were reminded during each submarine race that only one feature could vary (e.g., only volume varied during a volume demonstration). Children supplied the congruent organization, as one expects of Gestalt-like phenomena.

Findings of Experiment 3 show that children apply the principle of congruence to arbitrary feature relations such as the correlation between two separate shapes. The overall pattern of performance replicated that of Experiment 2, even though the features used in Experiment 3 (disc diameter, base length, and shadow size) differ notably from the features used in Experiment 2 (mass, volume, and sinking speed). Apparently, children's bias towards a congruent knowledge organization is a general principle, largely independent of the specific content of a particular domain. Further testing would be necessary, of course, to better establish boundary conditions of this principle of organization, for example whether it extends beyond physical relations to include the domain of social relations.

5.1. Congruence as transitive inference

What can account for children's bias towards congruence? Clearly, children do not add up the negative and positive relations to obtain an even number of negative relations. As Heider suggested, congruence may be more like a Gestalt principle similar to Gestalt principles postulated for perception (Lewin, 1936; Heider, 1958). Social attitudes that are congruent among each other (e.g., 'Mary likes Victor'; Mary likes smoking'; 'Victor likes smoking') may have a preferred Gestalt in some sense over incongruent attitudes (e.g., 'Mary likes Victor'; Mary likes smoking'; 'Victor *dis*likes smoking'). Could the same apply to naïve physics?

To answer this question, it may be helpful to step through a simpler case first: how children understand a *single* relation. Smith and Sera (1992) investigated the understanding of a single relation by asking participants to predict how arbitrary physical dimensions such as size and loudness relate to each other. For example, participants were presented with two drawings, a large mouse and a small mouse, and with two sounds, one loud and one soft. They responded as to which mouse should go with which sound, and which sound should go with which mouse. Participants 4–6 years and adults performed systematically across trials. For example, they matched the larger mouse with the louder sound and the smaller mouse with the softer sound. This outcome illustrates a more = more principle and suggests that children's intuitive understanding of relations corresponds to the mapping of the 'more' pole of one dimension with the 'more' pole of the second dimension (see also Lakoff, 1987).

This mapping of poles may also happen when children are explicitly taught about a physical relation. For example, children might understand a positive mass\volume correlation as 'more mass = more volume', and they might understand a negative volume\sinking-speed relation as 'more volume = less speed'. Thus mapping one pole to the other is a kind of mental short-hand or heuristic that can replaces the rather elaborate physical relation. Of course, this does not mean that children make use of the terms 'more' and 'less', or the terms 'mass', 'volume', and 'speed'. It merely means that these terms can be used to adequately describe children's performance: children distinguish among the dimensions mass, volume, and sinking speed (Smith et al., 1985), they distinguish the 'more' vs. 'less' poles of dimensions (Smith & Sera, 1992), and they relate these dimensions by mapping one pole to another. In the child's mind, a phrase such as 'more mass' might actually be captured by a single term such as 'heavy'. And the phrase 'more mass = more volume' might be captured in the child's mind by the compact symbolic expression 'heavy = large'. In abstract terms, physical relations may have forms such as A = B, where A represents one dimension's pole (e.g., 'heavy' or 'light'), and B represents the other dimension's pole (e.g., 'large' or 'small').

This notational scheme is useful because it can re-describe the sets of relations of the current experiments in ways that parallel abstract transitive inferences. Consider first congruent relations, such as those presented to children in Experiment 2 (negative mass\volume correlation, positive mass\sinking-speed relation, negative volume\sinking-speed relation). These relations can be re-described as 'more mass = less volume', 'more mass = more speed', and 'less volume = more speed', or in compact polar terms as heavy = small, heavy = fast, and small = fast. Substituting abstract symbols for the polar terms yields A (i.e., heavy) = B (i.e., small), A = C (i.e., fast), and B = C.

Once three relations are re-described in the abstract form of 'A = B, A = C, B = C', it turns out that *all* congruent relations have this same form, with the only difference being the polar content of A, B, and C. In Set 1 of Table 1, A = B is 'heavy = large', A = C is 'heavy = fast,' and B = C is 'large = fast'. In Set 2 of Table 1, A = B is 'heavy = large', A = C is 'heavy = slow', and B = C is 'large = slow'. And in Set 4 of Table 1, A = B is 'heavy = small', A = C is 'heavy = slow', and B = C is 'small = slow'.

Conversely, the abstract form of three incongruent relations is always 'A = B, A = C, and B = ¬C', where '¬' on the C term means the negation of a previously assigned abstract depiction. In Set 5 of Table 1, A = B is 'heavy = large', A = C is 'heavy = fast', and B = ¬C is 'large = slow' or 'large = not fast'. In Set 6 of Table 1, A = B is 'heavy = large', A = C is 'heavy = slow', and B = ¬C is 'large = fast' or 'large = not slow'. In Set 7 of Table 1, A = B is 'heavy = small', A = C is 'heavy = fast', and B = ¬C is 'small = slow' or 'small = not fast'. And in Set 8 of Table 1, A = B is 'heavy = small', A = C is 'heavy = slow', and B = ¬C is 'small = fast' or 'small = not slow'.

Transforming physical relations into a compact mapping of polar terms reveals a special case of transitive inference. Note that a commonly used transitive-inference task involves 'greater than' relations between two objects (i.e., if A > B, and B > C, then A > C) (e.g., Inhelder & Piaget, 1958; Bryant & Trabasso, 1971). However, transitive inferences are not limited to such relations and apply more widely to relations in general (e.g., Kliman, 1987; Frank, Rudy, Levy, & O'Reilly, 2005). Furthermore, transitive inference does not require explicit logical reasoning, given that transitive inferences have been documented in animals (e.g., von Fersen, Wynne, Delius, & Staddon, 1991; Davis, 1992; Wynne, 1998; Van Elzakker, O'Reilly, & Rudy, 2003). Congruent relations (A = B, A = C, and B = C) are always valid transitive inferences, and incongruent relations (A = B, A = C, and B = ¬C) are always invalid transitive inferences. For example, the logical conclusion of 'heavy = large' and 'heavy = fast' is the congruent relation 'large = fast' (cf., Set 1 of Table 1), not the incongruent relation 'large = slow' (cf., Set 5 of Table 1).

The detailed description given above makes it clear how the interlinking of three physical relations is logically parallel to transitive inference. This means that, children's bias towards congruence might be scaffolded by the same constraints that lead children to make successful transitive inferences. Incidentally, there are striking parallels between the procedures used in the current experiments and the procedures that yield successful transitive inferences in young children: both sets of studies over-emphasize relational information. In transitive-inference tasks, young children were found make correct inferences only after being presented with lengthy training of individual relations (e.g., Riley & Trabasso, 1974), or when non-relational information was largely eliminated (e.g., Kuenne, 1946; Jager Adams, 1978).

The same applies in the present experiments: children were presented with lengthy training of individual relations. For example, they were presented with pictures, objects, and a verbal description of the mass\volume correlation, in addition to completing four sorting trials on the basis of that correlation. And non-relational information was largely eliminated by the way the test items were constructed. Test items were picture cut-outs that corresponded to the real objects only in their relational information. Thus children were induced to apply relational rather than object-specific information in the testing phase.

Without over-emphasis on relational information, children might not have expressed congruence in their performance. This suggestion is consistent with Smith and Sera's (1992) findings. As mentioned already, children in that study guessed how arbitrary features were related to each other. They were not trained on how two features might be related to each other, and they were unlikely to have pre-existing beliefs about such relations. Furthermore, there was no transfer task that would have required children to use relational information. Indeed, the 4- to 6-year-olds in that study were not biased to produce congruent configurations.

5.2. Congruence as an explanation for naïve physics

A logically congruent belief is not necessarily a physically *correct* belief (irrespective of agreement with transitive inference). Children participating in the Incongruence conditions of the current experiments ignored the physically correct demonstrations and performed to create the congruent configuration. Bias towards congruence overrode physical evidence to the contrary. The implications of these findings go beyond simply demonstrating logical inferences in young children. They provide a new way to explain children's naïve and mistaken beliefs about physical regularities.

Most relevant here are children's mistakes with the concept of density, children's tendency to ignore an object's volume when determining its density. This mistake has been explained previously by postulating an undifferentiated mass–density concept that leads children to equate mass and density, and as a result to ignore the potential effect of volume on density (Carey, 1991). The current results suggest a different explanation.

Density is an inherently incongruent concept. Children are likely to believe that mass and volume correlate positively (either on the basis of specific experiences or on the basis of a simple more = more principle). Therefore, they are likely to believe that mass and volume have strictly parallel effects on density (i.e., that an increase in mass has the same effect on density as an increase in volume). Yet in reality, mass and volume have opposite effects on density: increases in mass (with no change in volume) lead to an increase in density, while increases in volume (with no change in mass) lead to a *decrease* in density. It is this inherent logical incongruence of the density concept, and not the inability to differentiate between mass and density, that might lead children to make mistakes.

The bias toward congruent beliefs readily accounts for other findings. First, take children's mistaken beliefs about how volume affects sinking speed when mass is held constant. Even after contradictory evidence, children believe incorrectly that a large object will sink faster in water than a small object (e.g., Penner & Klahr, 1996; Kloos & Somerville, 2001). The current results suggest that children only ignore contradicting evidence when the contradictory evidence supports an incongruent configuration of knowledge – an incongruent hypothesis, so to speak. Children are likely to believe that heavy objects sink faster than light objects (again, either on the basis of specific experiences or on the basis of a simple more = more principle; see also Kloos & Van Orden, 2005). Assuming in addition that heavy objects behave like large objects, children conclude that large objects must sink faster than small objects.

Second, take preschoolers' success in the density task of Kohn (1993). Kohn used a notably different methodology compared to studies that reported mistakes. In all studies that reported mistakes, children participated in initial tasks that required a focus on mass or volume alone. And during the experiment proper, children were presented with pairs of objects, so that comparisons in terms of mass (or volume) were made possible. In Kohn's (1993) study, by comparison, children were never required to focus on mass or volume alone, and they were presented with one object at a time during the experiment proper. Such a setting largely discouraged comparisons among objects in terms of mass (or volume) and hence did not elicit a belief that mass and volume correlate. Without such a belief, the organizing principle of congruence was missing – and with it the source of mistakes.

Finally, take previous reports of children who inverted their correct belief about effects of mass on sinking speed (Penner & Klahr, 1996; Kloos & Somerville, 2001; Kloos & Van Orden, 2005). These children came to believe that light objects sink faster in water than heavy objects without having observed such a relation prior to or during the experiment. The current results corroborate such reports: some children adopted the incorrect mass\sinking-speed belief even after having seen explicit demonstrations about how mass is related to sinking speed (Experiment 2). The explanation has again to do with children's congruent knowledge structures. Some children might have learned through observations that large objects sink more slowly than small objects. Knowing that large objects are also heavy, and therefore that heavy objects behave like large objects, children might have inferred that heavy objects must sink more slowly than light objects.

If mistaken beliefs about physical regularities come out of a bias in how children's knowledge is organized, then how can mistaken beliefs ever be overcome? For example, what would it take for children to learn the correct relations between mass and volume and density? Note that none of the children tested here acquired that understanding. Even those children who learned the correct effects of mass and volume on sinking speed showed dependence on the initially learned mass\volume correlation. To gain insight about how mass and volume are related to density, children must go beyond the organizing principle altogether. They must grasp that individual relations are physically possible, even when they are logically incongruent. Of course, this reorganization of knowledge may be difficult to achieve (cf., Wiser, 1995). After all, the equivalent leap, to give up a coherent set of beliefs in response to disconfirming evidence, poses at least as big a challenge to scientists as it does to children (Kuhn, 1962).

5.3. Conclusions

The current experiments draw together principles of organized knowledge and naïve physics. They shed light on previously unexpected origins for young children's reasoning about the physical world as well as their mistaken beliefs. The mistakes that characterize naïve physics and children's reluctance to change belief in the face of conflicting evidence may not be failures per se but principled by-products of knowledge Gestalts.

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