

Using Property Induction to Evaluate Understanding of Mixing

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Abstract

Although reasoning skills have been investigated in a number of different domains, very little is known about how children and adults use them in chemistry. Here, participants from 4 years to adults saw various mixtures presented using a standard property induction paradigm. The category and appearance of everyday materials were varied to assess the extent that participants use these features to inform their judgments about what happens when these materials are mixed with water. In general, the results followed similar patterns seen when this paradigm has been applied to other domains, with both category and appearance informing inductive generalizations. The findings contrast with interview-based measures of children's understanding of chemistry and offer an important addition to the field.

Keywords: property induction; chemistry; reasoning; cognitive development

Background

There is a growing consensus that children learn and reason about novel situations by basing their generalizations on their previous experiences (e.g., Wellman & Gelman, 1998). Children have extensive experience of chemistry in their everyday world, e.g., baking or rusting. However, there are few studies in cognitive science exploring children's reasoning about the chemical world. Here, we present a novel application of a property induction paradigm to investigate how primary school children (ages 4 to 11) reason about one basic chemical phenomenon - the mixing of different materials.¹

¹ The terms used in this paper are compatible with standard terminology used by chemists in technical writing. Items such as soap, coconut, or sugar are a mixture of substances and are not considered pure 'substances' by chemists. Instead, chemists refer to these items as 'materials'. For simplicity, the term 'materials' is used here to refer to all items rather than having to distinguish between materials and substances. This terminology does not fit squarely within the typical cognitive science framework where 'substances' might be used to indicate different categories and 'materials' used to refer to the stimuli and props used in an experiment. In addition, when materials are added to water there may or may not be a chemical reaction, depending on the makeup of the materials involved. Therefore, we use the term 'mixing' to capture the process for all items, regardless of the chemical outcome of the mixing process.

The focus of this study is mixing because it is one of the earliest chemical phenomena children are deemed capable of grasping (e.g., Au, Sidle, & Rollins, 1993; Johnson, 2000; Rosen & Rozin, 1993) and because very little work exists in this area (Çalýk, Ayas, & Ebenezer, 2005). Most of the few existing studies have used interviews. The results of these interviews suggest that young children attend almost exclusively to what they can see, i.e., the macroscopic properties of the materials (Arnold, Moye, & Winer, 1986; Ebenezer & Erikson, 1996; Haider & Abraham, 1991) and have little or no conception of the particulate nature of matter (Liu & Lesniak, 2006; Nakhleh & Samarapungavan, 1999; Renström, Andersson, & Marton, 1990). Briefly, the particulate nature of matter refers to the idea that materials are made up of invisible, sub-microscopic particles, with molecules being the smallest particles of most materials. Some knowledge of the particulate nature of matter is necessary to understand materials and how they interact with each other; naïve (incomplete or incorrect) understanding of particles likely leads to misconceptions of chemical phenomena. The assumption is that because young children are not able to explain the particulate nature of matter or the microscopic properties of materials that they lack the ability to reason adequately about materials

One issue with these findings is that the interview method relies on children having the appropriate language of chemistry to be able to explain the phenomena. As a result, it may be the case that children's abilities in this area have been greatly underestimated. Extensive studies of naïve physics and naïve biology indicate that children's reasoning abilities about these science phenomena surpass their abilities to explain them verbally. Tasks that are not reliant on verbal ability indicate that even infants have some understanding of physics (Wellman & Gelman, 1998). For example, infants know that solid objects cannot just appear/disappear or move through physical barriers (Spelke, Breinlinger, Macomber, & Jacobson, 1992), are distinct from one another (Xu & Carey, 1996), and once put into motion travel over distances related to the force of that motion (Kotovsky & Baillargeon, 1998). These tasks indicate young children do have some appreciation of the properties of materials; 3-year-olds know that wooden pillows are hard (Kalish & Gelman, 1992) and 4-year-olds know that material is conserved if the object is broken up

(e.g., a plastic toy taken apart is still plastic even if it no longer operates as a toy; Smith, Carey, & Wiser, 1985).

The success of these language-sparse experimental paradigms in uncovering the foundations of young children's emerging understanding in naïve physics and biology might suggest that young children can make sense of chemical phenomena. Here, we use a language-sparse property induction paradigm to study early chemistry reasoning. Briefly, the property induction paradigm investigates how children use category and appearance information in their generalizations of natural kinds, typically biological kinds (Gelman & Markman, 1986; Gelman & Markman, 1987). For example, Farrar, Raney, & Boyer (1992) showed 5- to 10-year-old children a familiar target object with its familiar name (e.g., egg) and taught them a novel property about that object (e.g., 'has mitochondria inside'). Next, children were asked whether the four test items below also had that novel property:

1. Same category, same appearance (e.g., plain egg);
2. Same category, different appearance (e.g., spotted egg);
3. Different category, same appearance (e.g., snow ball);
4. Different category, different appearance (e.g., leaf).

At all ages, generalizations depended both on category and appearance, but how children relied on these cues changed with age. Pre-school children generalized more to objects in the same category with the same appearance than to the other items; in other words, they thought the typical cue correlation was necessary. Second graders generalized more to objects that matched in category and appearance than to objects matching in only one cue than to objects matching in neither cue; that is, they realize that category and appearance are separable predictors. Only fourth graders generalized more to same category, different appearance items than to different category, same appearance items, realizing that category was a better predictor than appearance. This mature pattern appeared even for second graders in a second study varying knowledge of the categories/properties in question, but only when children reasoned about known categories/properties. Generalization about materials may include more features than category and appearance. For example, 8-year-olds seem to generalize more often to items with matching causal information compared to perceptual features and 5-year-olds seem to be able to make use of causal information when it is not in competition with physical features (Hayes & Thompson, 2007). This distinction may be relevant for chemistry where the causal factors that determine mixing outcomes may not correspond to perceptual features. The results from these property induction studies have indicated that children as young as 2 years are not limited to appearance-based reasoning when categories/properties are well known (Gelman & Coley, 1990), but variations in knowledge continue to play a vital role at older ages.

Given the success of this paradigm in furthering the understanding of young children's reasoning, it seems well suited as an application for the chemical phenomena investigated here – mixing. More specifically, do children

generalize from one mixture outcome to another if the substances involved are of the same category or of the same appearance? How does this depend on age and on children's knowledge of the substances involved?

In contrast to studies of biological properties, generalization of mixture properties does not depend on category only, but on appearance as well. Mapping the category and appearance properties onto chemistry, it might be useful to think of categories in chemistry as relating to materials and appearances in chemistry as relating to forms like powder, granule or larger chunks. Whether different materials dissolve in water or not depends on a variety of factors related to molecular structure. For instance, water is polar and can break other polar or ionic materials like salt (NaCl) apart, but not non-polar or covalent materials like sand (SiO₂); roughly, like dissolves like. How different forms of a material mix with water might depend on factors related to surface area. For instance, table salt (NaCl, in granular form) usually dissolves more quickly in water than rock salt (NaCl, in a large chunk) because it has a greater surface area. As such, in addition to examining the role of language in children's reasoning about basic chemical phenomena, the current design allows for an investigation of whether children's generalizations about chemical properties are similar to those in other domains. Specifically, will reasoning about chemistry follow both material (category) and form (appearance) cues in the same way as for biology, will there be a different pattern for chemistry, reflecting domain differences in cue efficacy, or will young children remain appearance-bound, as predicted by the findings from interview studies?

Method

Participants

A total of 142 participants ($N_{female} = 81$) took part in this experiment. There were 122 children recruited from schools in eastern England, including 24 children from reception ($M = 4.87$ years, $SD = 0.35$, $N_{female} = 11$), 32 children from year two ($M = 6.62$ years, $SD = 0.46$, $N_{female} = 19$), 33 from year four ($M = 8.60$ years, $SD = 0.41$, $N_{female} = 15$) and 35 from year six ($M = 10.74$ years, $SD = 0.28$, $N_{female} = 21$). In addition, 20 adult participants were recruited from the university and local community ($M = 26.45$, $SD = 6.70$, $N_{female} = 15$). For simplicity, these different age groups are referred to here as *5-year-olds*, *7-year-olds*, *9-year-olds*, *11-year-olds*, and *adults*. Adults were paid £10 for their participation and represented a range of chemistry experience. Children were invited to dress up as scientists for the duration of the study and were given stickers and their schools given a special science presentation by a local science outreach program. The participating schools were typical schools in terms of their range of student abilities and backgrounds according to publically available government data (www.ofsted.gov.uk).



Figure 1. An example of a target. The picture on the left shows the water and the target (e.g., granulated brown sugar) before mixing. The picture on the right shows the water and target after they were mixed.

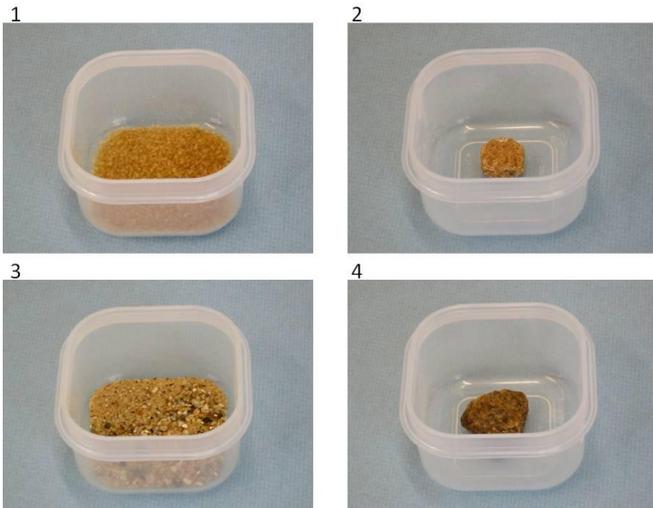


Figure 2. An example of a set of probes: (1) same material, same form (e.g., granulated brown sugar); (2) same material, different form (e.g., brown sugar cube); (3) different material, same form (e.g., sand); and (4) different material, different form (e.g., a pebble).

Materials

Everyday items (e.g., sugars, salts, sand, etc.) were selected as stimuli because children may reason better about familiar content and for safety reasons. Twelve sets of items were chosen, with each set including a target and four probes (see Table 1). The probes followed the conditions mentioned above: (1) same material, same form; (2) same material, different form; (3) different material, same form; and (4) different material, different form.

Several constraints were imposed on the selection of the targets and probes based on pragmatics and the experimental design: (1) the target and probes were safe and appropriate for use with young children; (2) the target-probe pairs had similar appearances for their matching forms (solid, granule, or powder); and (3) the targets and probes were balanced in terms of their outcomes when mixed with water. When controlling for mixing outcomes it was noticed that long names, (e.g., antacid) were often associated with exciting outcomes such as fizzing. To avoid this possible confound

some items were given alternative names². Finally, the relative mass and volume of the targets and probes were as similar as possible so that these perceptual features would not act as additional cues to the outcomes. Transparent 400mL plastic beakers (see Figure 1) were used to show the mixing of each target with water. The beakers were filled with 250mL of water and had lids to allow mixing of the targets with the water without risk of spillage. The probes were presented in transparent 140mL plastic containers (see Figure 2), sealed with clear plastic lids for safety.

Procedures

Participants sat opposite the experimenter at a table in a quiet area of their primary school or university. A clear plastic beaker with water was placed on the table and identified as water. A transparent plastic tub containing the target was displayed and identified for the participant, using the phrase “See this tub? This tub has [target name]. I’m going to mix the [target name] with the water.”

All items were named for the participants. In order to ensure no cues about the type of material could be implied from the instructions, mass/count words were not used (e.g., “This is a vitamin.” or “This is some sugar.”). Instead, only general names were given (e.g., “This is vitamin.” or “This is sugar.”). The form of the target and probe were not mentioned.

The target was added to the water, the beaker was sealed and it was turned upside down once to facilitate mixing. Participants were asked to describe what happened both to the target and to the water. This step ensured they were attending to the mixing.

Table 1: List of Target and Probe Materials

<i>Target Form</i>	<i>Target Material</i>	<i>Probe Material</i>
Solid	Chalk	Lolly
	Chocolate	Almond
	Vitamin	Sweet
	Paint	Incense
Granule	Peppercorns	Candy
	Bath Bomb	Wax
	Sugar	Stone
	Coffee	Stock cube
Powder	Coconut	Soap
	Antacid	Washing Soap
	Salt	Rice
	Kool-Aid	Play-Doh

After mixing the target with water, the experimenter displayed and identified each of the four probes, one at a

² Antacid became ‘meds’, bath bomb and washing powder became ‘stuff for the bath’ and ‘Stuff for the Wash’ respectively. Peppercorn was shortened to ‘pepper’, and stock cube was ‘stock’. ‘lolly’ was a short stick of candy.

time in a pre-established randomized ordering. For each probe participants were asked if it would do the same as the target using the phrase 'See this tub? This tub has [probe name] in it. Do you think this would do the same as [target name] if I put it in water?'

Participants were instructed to give "Yes" or "No" replies. Simplifying the required responses in this way was important in order to make the task accessible for the youngest participants. For the younger groups two sheets of paper were also available, green and red, with 'yes' and 'no' written on them respectively. Children could point to these if they did not give a verbal response. Only one child made use of these sheets. If participants did not give a specific 'yes' or 'no' response, the question was repeated to prompt a 'yes' or 'no' answer. Sessions were video recorded so that replies could be verified and confirmed off-line.

The target remained in view on the table mixed with the water while the participants saw the probes. After each of the four probes was presented, the target and water were cleared out of view before the next set of items was presented.

There were 12 sets of items each containing a target to be mixed with water and four probes for a total of 48 trials. Both the order of the 12 sets and the order four probes within each set were presented pseudo-randomly. The youngest group always completed the study in two separate sessions.

Results

The proportion of "Yes" responses given by the participants to the probes were analyzed using a $5 \times 2 \times 2$ repeated measures ANOVA with the between-subjects factor of age group (5-year-olds, 7-year-olds, 9-year-olds, 11-year-olds, and adults) and the within-subjects factors of material (same vs. different from the target) and form (same vs. different from the target). This ANOVA was conducted using the restricted maximum likelihood technique (REML; Bagniella, Sloan, & Heitjan, 2000). There were no overall significant differences among the three forms (powder, granule, or solid), making it feasible to combine them together and focus the analyses on same vs. different form only.

There was a significant effect of both material, $F(1, 139.1) = 445.44, p < .0001$, and form, $F(1, 139.2) = 418.56, p < .0001$, as well as a significant interaction between material and form, $F(1, 139.3) = 119.42, p < .0001$ (See Figure 3). More specifically, participants responded "Yes" most often when the probe was the same material, and same form as the target ($M = .96, SD = .21$), followed by probes that were the same material and different form ($M = .59, SD = .49$), probes that were a different material and same form ($M = .49, SD = .50$), and probes that were a different material and different form ($M = .30, SD = .46$). Post-hoc tests using Tukey's HSD indicated that each probe type was different from the others.

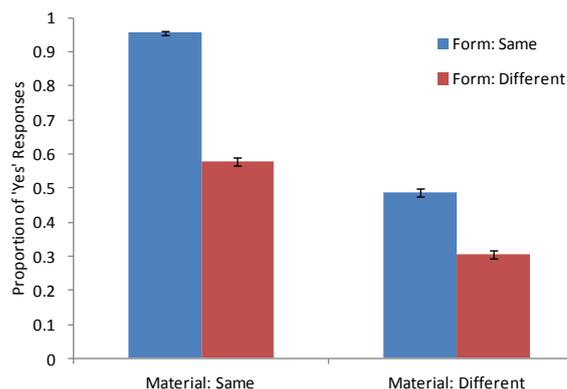


Figure 3. The mean proportion of "Yes" responses made to the same and different materials and forms across all age groups.

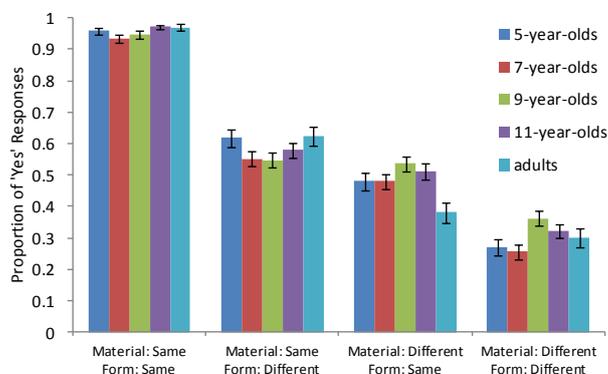


Figure 4. The mean proportion of "Yes" responses made to the same and different materials and forms by each age group.

The main effect of age group was not significant, $F(4, 139.1) = 0.89, p = .47$. Similarly, age group did not interact significantly with material, $F(4, 139.1) = 2.03, p = .09$, form, $F(4, 139.1) = 1.15, p = .34$, or material and form combined, $F(4, 139.2) = 1.53, p = .20$ (see Figure 4).

Discussion

This paper presents a novel adaptation of the property induction paradigm to explore how children reason about the chemical process of mixing. The design was created in order to use language-sparse methods as a way of further examining children's reasoning in this domain by addressing whether: (1) young children display a better understanding of mixing processes when assessed using a language-sparse method compared to interviews; and (2) whether children differentially attend to the category (material) or appearance (form) of materials when generalizing about mixing.

In terms of the first question, the results confirm that young children's reasoning about these materials does not differ from older children and adults in terms of mixing in

this context. These findings are consistent with other property induction studies, but are contrary to the results of interview studies (Gelman & Markman, 1986; Gelman & Markman, 1987; Liu & Lesniak, 2006; Au, Sidle, & Rollins, 1993). As such, there is some indication that this type of language-sparse methodology might be useful in further exploring how young children reason about other chemical phenomena.

In relation to the second question, participants of all age groups attend to category and appearance when making generalizations about mixing. The presence of this finding for the youngest age group suggests that even young children bring their everyday reasoning skills to understanding chemistry despite not yet being able to articulate sophisticated explanations. The findings presented here replicate the overall pattern found with property induction studies in other domains (e.g., Gelman & Markman, 1987). Specifically, the category seems to have more influence than appearance on the generalizations that were made.

However, these findings are distinctive to property induction studies in other areas. Specifically, this study did not replicate the common finding of age related differences in the use of category and appearance. In a chemistry context like that presented here, both features seem to be influencing generalizations, whereas in other studies from the domain of biology the categorical information becomes more important for generalizations in older children than younger children (e.g., Farrar et al., 1992).

One explanation for the discrepancy between the results found here and other property induction studies might be that this task used naturalistic materials and actual mixing events, whereas most of the previous studies used pictures, words or text (Farrar et al., 1992; Gelman & Coley, 1990; Gelman & Markman, 1986; Gelman & Markman, 1987; Hayes & Thompson, 2007). More specifically, these previous studies mostly frequently used artificially selected stimuli with a constrained set of properties that allowed for a limited number of inductions, whereas the materials used here are more ecologically valid but they do include a wider variety of properties and more possible inductions.

Using real materials might have inadvertently allowed participants to attend to properties other than the category and appearance properties explicitly examined here (e.g., the density of objects could have been assumed by participants to have played a role in the outcome). In contrast, when experimental stimuli are created to vary only on a limited set of properties, then participants may base their generalizations more on the specific properties for which these artificial stimuli were designed to control. Thus, the inherent complexity of real-world materials might have prevented well-controlled and systematic studies of reasoning about chemistry. This language-sparse design provides a platform from which additional studies might be developed that control for the wide variety of features that may play a role when natural stimuli are used in property induction studies, while still being more ecologically valid.

It may be the case that children exploit multiple redundant cues in their natural environment, so the pattern found here may be indicative of their reasoning in their everyday lives.

Another reason for this finding in chemistry, but not biology might be due to domain-specific differences in the way chemistry information is processed. It could be the case that reasoning skills are applied differently in the biological and chemical contexts because the features that help in terms of generalization have different predictive validity.

In chemistry, appearance might be both an unreliable predictor and necessary for making a prediction. Firstly, appearance alone is generally an unreliable predictor of category. For example, white powder can be any number of different materials with a wide range of possible chemical properties. Secondly, it is difficult to make a prediction about the outcome based on the knowledge of the category without information about appearance. For example, aluminum is inert as a solid block, but easily combusts in powdered form. In contrast, in biology, appearance might be a reliable predictor of behavior when it predicts category membership (e.g., wings might predict bird and flying).

Most property induction studies introduce unreliable correlations amongst features like appearance and category and assuming that biology naturally includes more reliable correlations amongst these features, then it could be the case that property induction studies introduce unnatural reasoning settings. As such, the age difference apparent in biology generalizations may reflect children's growing understanding of what to do when the correlations they experience in their everyday lives are broken by our experimental designs in property induction. On the other hand, in chemistry, the correlations are naturally unreliable, matching the usual property induction design. Thus, the property induction paradigm might be more representative of naturalistic reasoning in chemistry but not biology. If that were the case, then the more mature reasoning seen in this chemistry context might be related to the match between the experimental design and children's everyday experiences rather than the differences inherent to reasoning about biology and chemistry.

This aspect of chemistry raises an intriguing perspective on development of categorization and reasoning skills. Cognitive science includes a large body of studies investigating the basic building blocks of cognition with which children learn about the world. In physics, biology, and psychology evidence has suggested that children generalize existing knowledge to extend their ability to reason about the world. A debate remains about the origins of these basic reasoning skills. Most areas of reasoning struggle to separate the question of how much of reasoning is dependent upon domain-specific experiences and how much is due to domain-general strategies. Chemistry may offer a unique perspective for this debate. Like physics, biology, and psychology, children are exposed to chemical phenomena throughout childhood, but the differences between these domains in terms of predictive validity of features might provide a new direction for further study.

If it is indeed the case that children are sensitive to the idea that different cues are meaningful in biology versus chemistry, then it could be the case that children are bringing very sophisticated reasoning skills to their attempts to understand chemistry. However, this is the first study in this area and other relevant cues (e.g., density, naming, etc.) should to be explored before firm conclusions can be made.

In sum, this novel application of the property induction paradigm to chemistry raises important questions about the development of reasoning skills in chemistry and further offers directions of research to address key questions of how children learn to reason about the world. The question of how abstract reasoning skills develop is a core issue for education. Previous research into young children's understanding of chemistry has relied upon language-based measures. This study offers a more sensitive measure of chemistry reasoning that is not constrained by a child's language development. The findings presented here might be useful in re-evaluating the assumptions that educators make about the reasoning skills children bring to chemistry learning and could be applied to develop more effective ways of learning for chemistry students of all ages.

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