

Why Teach *How Things Work*? Tracking the Evolution of Children's Intuitions about Complexity

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Abstract

Mechanistic information can be characterized as the interacting causal components underlying a phenomenon - in short, how something works. Children and adults are notoriously poor at learning, remembering, and applying mechanistic information, so it comes as no surprise that the wisdom of teaching mechanism has come under increasing scrutiny in science education. However, while a rich memory for mechanistic details may be out of the average student's grasp, we argue that exposure to mechanism does not leave students empty-handed. Instead, it refines their intuitions about science and the world in significant ways. For the current study, we focused on one kind of intuition in particular: beliefs about causal complexity. Children ages 6-11 rated the complexity of a heart and a lock and were then given either mechanistic or non-mechanistic information about them. Afterwards, they were asked if their intuitions about complexity had changed and if so by how much. Three weeks later, children were asked again about their intuitions about complexity. Crucially, children who were given mechanistic information demonstrated a significantly greater shift in their assessments of complexity for both the heart and door lock compared to their counterparts who were given non-mechanistic information. This contradicts the notion that mechanism provides learners with few benefits while also demonstrating how mechanism can be a powerful force in shaping children's intuitions.

Keywords: causal mechanisms; explanation; complexity intuitions; meta-knowledge; cognitive development

Introduction

Humans possess cognitive systems that enable them to grasp causal relations around them. As early as eight months, children are able to predict outcomes of novel causal events (Sobel & Kirkham, 2006) and less than a year later, they are capable of making successful causal interventions (Gopnik et al., 2004; Gopnik, Sobel, Schulz,

& Glymour, 2001), even for causal relationships defined by abstract relational properties (Walker & Gopnik, 2014).

However, given the rapid growth of human knowledge and technology in the modern era, many of the known causal relations in the world are becoming increasingly complex and inaccessible (Arbersman, 2016). Except for relevant experts, this burgeoning set of causal patterns presents a challenge for how laypeople grasp the causal structure of the world around them. Most adults, for example, are unable to give even a basic explanation of the mechanisms underlying everyday objects like a door lock or a clock, let alone more complicated objects like a car engine or a computer. Similarly, we have a surprisingly poor understanding of the mechanisms underlying the functioning of living things and even how our own bodies work. To make matters worse, laypeople often believe they possess detailed mechanistic knowledge about the world despite having next to none, a phenomenon known as the Illusion of Explanatory Depth (IOED) (Alter, Oppenheimer, & Zemla, 2010; Rozenblit & Keil, 2002). These major gaps in adult causal knowledge occur not just in recall but also in recognition. For example, many adults fail to recognize the difference between a schematic of a functional bicycle and one that is completely inoperable (Lawson, 2006). In children, this illusion is present to an even greater degree (Mills & Keil, 2004).

Our cognitive mechanisms dealing with causality seem to fall short in keeping vivid representations of somewhat complex causal patterns. Despite this tendency to forget mechanistic information, humans however show a certain curiosity about *how things work*. Children ask for mechanistic information about things they encounter, usually phrased as ubiquitous "why" and "how" questions, starting around three years of age (Callanan & Oakes, 1992), and they are often relentless in their questioning until

they receive a mechanism-oriented response (Chouinard, 2007; Frazier, Gelman, & Wellman, 2009). This preference for mechanistic explanation persists into adulthood (e.g., Ahn et al., 1995; Johnson & Ahn, 2015). In short, despite our poor ability to learn, retain, or recall mechanistic information, people of all ages often show considerable interest, and at times an outright preference, for mechanistic information.

Mechanisms in the Classroom

A natural reaction to the massive decay in our retention of mechanism is to downplay the need to learn it at all and refocus science education on topics such as the nature of science, epistemological stances, and methodology (Osborne et al, 2003). After all, even if students enjoy learning information about how things work, they fail to retain it; shouldn't we focus on teaching them things they can actually remember? Without denying the importance of topics like epistemology, we argue there are insidious costs in failing to expose children to rich mechanistic details. At root, the benefits of mechanism lie not with the details learned, but with the higher order intuitions acquired and sharpened as a result of teaching mechanism.

More precisely, we argue the bulk of cognitive gain from exposure to mechanism occurs at the "meta-knowledge" level (Kominsky, Zamm & Keil, in press). Even if we have no idea how a car engine actually works, we do have some intuitions about the underlying mechanisms: for example, we might think it involves metal and plastic components as opposed to organic parts, that it is extremely complex and difficult to learn about, and more crucially, we may also be able to tell apart experts from laypeople when hearing them talk about the mechanism. Thus, even if we do not know the details of how an object works, we often have surprisingly accurate intuitions about how much "stuff" is in a mechanism, how complicated a mechanism is, and whose expertise we can rely on.

Indeed, despite the decay of knowledge about the mechanism itself, some kind of mechanistic information seems to persist: mechanistic information influences causal reasoning (Ahn et al., 1995; Schlottmann, 1999), and mechanism may constrain Bayesian causal learning by reshaping priors about what causal links exist or how strong they are (Griffiths & Tenenbaum, 2005, 2009). Thus, some aspects of mechanistic information are preserved, but are neither detailed nor complete (e.g., DiSessa, Gillespie, & Esterly, 2004; Straatemeier, van der Maas, & Jansen, 2008; Vosniadou, 2002). If most individuals do not retain deep, integrated understandings of "how things work", what kind of mechanistic knowledge does persist?

The current study pursues the beginnings of an answer to this broad question by focusing on intuitions about complexity. Intuition about causal complexity is a good candidate for a kind of meta-knowledge that would persist after memory decay. For instance, one may have a strong feeling that the mechanisms underlying the human ear or a

clock are highly complex without being able to give any accurate descriptions of the mechanism itself.

To summarize, we argue that mechanism instruction is essential to STEM learning as long as we acknowledge what is actually retained over time and what is not. Expecting children to retain fine-grained mechanistic details is simply an unrealistic goal. Instead, focusing mechanistic exposure on building richer meta-mechanistic knowledge establishes both achievable and useful goals. In particular, we argue that exposure to mechanism is a necessary pathway to other forms of more enduring representations such as intuitions about causal complexity, the focus of the current study.

Experiment

Stimuli

We chose a heart and a door lock as stimuli because they look quite simple from the outside while having a somewhat rich causal mechanism on the inside. In order to control for a potential reaction of surprise to hidden complexity in the mechanistic condition, the verbal information provided in the non-mechanistic condition included, both for the heart and the door lock, some surprising facts such as "people think that the heart is red but actually the heart itself is dark brown".

The number of words of verbal information presented to the children was matched between the mechanistic (212 words) and non-mechanistic condition (208 words). We also created the text stimuli so that the non-mechanistic information was more superficially complex than the mechanistic information (e.g., Flesh Reading Ease: 79.97 for the non-mechanistic text and 91.53 for the mechanistic text).

Predictions

We had no predictions about the age of children in this study but included this variable in our analysis as exploratory.

H1) Exposure to mechanistic information should shift children's intuitions of complexity.

H2) The children who underestimate complexity should move towards higher complexity judgments once provided with mechanistic information.

H3) This shift towards higher complexity should still be observable three weeks later.

Methods

Participants We recruited 144 children from an elementary school in the New Haven, CT area. Our sample was somewhat atypical in two ways: the elementary school is situated in a low SES neighborhood and the elementary school has a strong focus on science (classified as a STEM school). Our sample consisted of 20 Kindergarteners, 15 first graders, 15 second graders, 41 third graders, 34 fourth graders and 18 fifth graders. The experimenters interviewed child participants individually for about ten minutes in a

quiet spot in the school. All participants were rewarded with a small toy.

Training Phase Children were told they would be presented with pictures of things and would be asked if they thought the thing is simple or complicated. Participants were explicitly told both at the very beginning and just after the training phase “there are no right or wrong answers, I just want to know what you think”.

The two training questions were designed to introduce children to our complexity scale and to have a clear criterion of exclusion. The training consisted in showing children black and white drawings of an hourglass and grandfather clock. In order to prevent children’s intuitions about complexity being driven only by the ease of use - as previous pilot experiments suggested - children were told that “both these two things are easy to use but the way they work is really different”, followed by a short justification of why the hourglass is simple (“It’s just sand going down”) and why a grandfather clock is more complicated (“It has many gears and pendulums inside that all work together to move the hands on the clock”).

Children were then presented with black and white drawings of a bicycle and a motorcycle. For each, they were asked whether they thought it was simple or complicated. Depending of their first answer, they were asked if they thought it was “really” simple/complicated or “kind of” simple/complicated. Children’s answers on each entity can thus be coded on a 2 point scale (simple or complicated) or on a 4 point scale: really simple (0), kind of simple (1), kind of complicated (2) and really complicated (3).

Test Phase Just after the training phase, children were presented with a black and white drawing of a heart or a door lock (order of presentation was counterbalanced). They were asked whether they thought the entity was simple or complicated in the same way as in the training phase. All participants were then told that some information about the entity would be presented to them. Half the participants were randomly assigned to the mechanistic condition and the other half were assigned to the non-mechanistic condition. Participants in the mechanistic condition were presented with pictures of the inside of a heart and of a door lock, along with some verbal information about how it works. Participants in the non-mechanistic condition were presented with pictures illustrating some facts about the heart or door locks along with corresponding verbal information matched in length to the mechanistic condition.

After hearing the information, all participants were reminded of their initial complexity judgment and asked if they wanted to keep their answer or if they thought a heart / a lock was more complicated/simple than they had previously thought. Depending on their answer, they were then asked if it is much more complicated/simple than what they thought before or a little bit more complicated/simple than what they thought before. Their shifts in complexity judgments were coded with a 5 point scale: much more

simple (-2), a little more simple (-1), still what I think (0), a little bit more complicated (+1) and much more complicated (+ 2). The exact same procedure was repeated with the second entity.

Retention Test, Just after the complexity judgments, all children were asked a series of questions about the information (mechanistic or non-mechanistic) that had been given to them. This test was used to assess the children’s retention of the information that was just presented to them in order to measure retention scores on the exact same test three weeks later. Questions were either “yes – no” questions (0.5 point); questions about quantity or colors (1 point) or open-ended (2 points). In the mechanistic condition, scores could range from 0 to 12.5; in the non-mechanistic condition, scores ranged from 0 to 18.5. All the scores were normalized to range between 0 and 1. Based on the Yes/No questions, we calculated the chance level for each condition: 0.10 in the mechanistic condition and 0.04 in the non-mechanistic condition.

Exclusion The 24 children (17%) who, during the training phase judged a bicycle as more complex than a motorcycle were excluded from the analysis. In addition, since 50% (9) of the kindergarteners failed to judge a motorcycle as more complex than a bike, all the kindergarteners were excluded from the analyses. The following analyses apply to a sample of 111 children.

Results

Analysis Children were grouped into three age groups: 1st and 2nd graders ($N = 26$), 3rd graders ($N = 37$), 4th and 5th graders ($N = 48$).

Our analyses focus on three dependent variables, the absolute value of shift, the raw value – direction -- of shift, and the direction of long-term shift three weeks after the initial measure. We looked at the effect of three independent variables. Two variables were linked to our hypotheses, condition (mechanistic and non-mechanistic) and initial rating (which we grouped in two levels - simple or complicated - instead of the 4 measured ones - kind of / really - in order to increase our statistical power). The third variable was age group (1st and 2nd graders, 3rd graders, and 4th and 5th graders), which was exploratory. Only the interactions with condition were tested.

Initial complexity judgments were significantly higher for the heart ($M = 1.7$, $SD = 1.14$) than for the lock ($M = 0.96$, $SD = 1.03$), paired t-test $t(110) = 4.79$, $p < .001$. In the following analyses the two entities were analyzed separately.

Absolute value of shift For both the heart and the lock, we performed a 2 (condition) x 2 (initial rating) x 3 (age groups) fully between-subjects Analysis of Variance (ANOVA) with the absolute value of shift as DV. For both entities, the ANOVAs revealed a main effect of condition (Heart: $F(1,103) = 4.13$, $p = .04$, $\eta_p^2 = .04$; Lock: $F(1,103)$

= 17.78, $p < .001$, $\eta_p^2 = .14$). Those main effects of condition came from a larger absolute value of shift for children in the mechanistic condition both for the heart ($M = 1.14$, $SD = 0.67$ versus $M = 0.87$, $SD = 0.75$) and the lock ($M = 1.22$, $SD = 0.60$ versus $M = 0.69$, $SD = 0.77$).

A main effect of initial ratings was also found for both entities (Heart: $F(1,103) = 4.10$, $p = .05$, $\eta_p^2 = .04$; Lock: $F(1,103) = 4.07$, $p = .05$, $\eta_p^2 = .03$) corresponding to a larger absolute value of shift for participants initially judging an entity as simple. No other main effects or interactions were significant for either entity.

Direction of shift For each entity, we performed a 2 (condition) x 2 (initial rating) x 3 (age groups) fully between-subjects ANOVA with the shift in complexity judgment measured just after children were exposed to some information as a DV (from -2 to +2) (see Fig. 1).

For the heart, a significant interaction between the initial rating and the condition was found ($F(1,103) = 5.56$, $p = .02$, $\eta_p^2 = .05$). To further explore this interaction, two post-hoc two sample t-tests with Bonferroni adjusted alpha levels of .025 per test (.05/2) showed that for the children who initially judged the heart as simple, being exposed to mechanistic information resulted in an average shift towards higher complexity ($M = 0.70$, $SD = 1.36$) compared to children exposed to non-mechanistic information ($M = -0.21$, $SD = 1.23$; $t(39.7) = 2.26$, $p = .02$). As for children who initially judged the heart as complex, there was no difference in complexity shift between the mechanistic ($M = -0.09$, $SD = 0.14$) and non-mechanistic condition ($M = 0.14$, $SD = 1.12$; $t(66.4) = -0.83$, $p = .41$).

For the lock, the same analysis did not show any significant effect or interaction.

Analyses of High Initial Retention Participants Median scores were calculated on the retention task for each condition, entity, and crucially for each of the three age groups in order to avoid having mostly older children in the high retention group. In order to explore the possibility that some participants were not paying sufficient attention to the task or had difficulty understanding the material presented to them, children scoring lower than the median in each of the groups were dropped from the sample. All the following analyses are similar to the analyses presented before but includes only the high retention half of our sample (for the heart, $N = 35$ in the mechanistic condition and $N = 29$ in the non-mechanistic condition; for the lock $N = 39$ and $N = 31$ respectively).

In terms of absolute value of shift, results for the high retention group were similar to those of the entire sample with a significantly larger shift in the mechanistic condition (main effect of condition. heart: $F(1,56) = 5.5$, $p = .02$, $\eta_p^2 = .08$; lock: $F(1,62) = 6.1$, $p = .01$, $\eta_p^2 = .09$). As before, a main effect of initial judgment was found only for the heart ($F(1,56) = 4.2$, $p = .05$, $\eta_p^2 = .06$) but not for the lock ($F(1,62) = 2.6$, $p = .11$, $\eta_p^2 = .04$), likely due to a lack of power.

Despite having our sample size cut in half, results on the direction of the shift and on the final ratings were even more in line with our initial hypotheses.

With respect to the direction of the shift for the heart, the ANOVA revealed a significant interaction between condition and initial rating (Heart: $F(1,56) = 9.92$, $p = .01$, $\eta_p^2 = .10$). For the lock, as opposed to the same analysis with the entire population, the interaction between condition and initial rating was at trend level ($F(1,62) = 3.97$, $p = .09$, $\eta_p^2 = .04$). A main effect of initial judgment was also found for the lock ($F(1,62) = 4.5$, $p = .04$, $\eta_p^2 = .06$) but not for the heart ($F(1,56) = 2.2$, $p = .14$, $\eta_p^2 = .04$). As displayed in Figure 1, one pattern seems similar for both entities: children who start by judging the entity as simple in the mechanistic condition tend to increase their complexity rating to a greater extent compared to both children in the non-mechanistic condition as well as children who start by judging the entity as complicated.

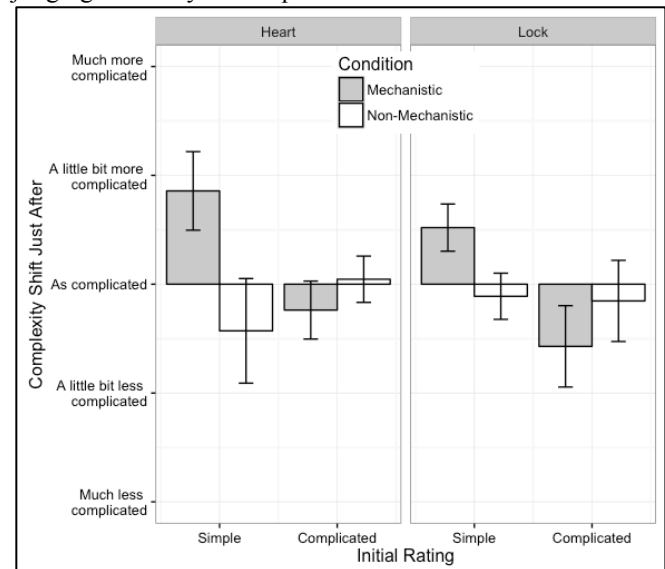


Figure 1: Average value of shift (y-axis) with standard errors bars for the high initial retention group, in the mechanistic (grey) and non-mechanistic condition (white) as a function of initial complexity judgment (x-axis). Results for the heart and lock are presented on the left and right panels respectively.

Shift in complexity three weeks later We again asked children about their intuitions of complexity three weeks later using the same methodology. Twelve children (11%) had changed schools or were absent during the times we were testing. Therefore, the following analyses apply to a sample of 99 children.

For each entity, we performed the same 2 (condition) x 3 (age group) x 2 (initial rating) with the shift between children's initial rating and their rating three weeks later as a dependent variable (*long-term shift*).

For both the heart and the lock, we found main effects of initial rating (heart: $F(1,91) = 44.9$, $p < .001$, $\eta_p^2 = .31$; lock: $F(1,91) = 33.6$, $p < .001$, $\eta_p^2 = .27$). A main effect of

condition was found at trend level for the heart ($F(1,91) = 3.0, p = .08, \eta_p^2 = .02$), but not for the lock.

When performing the same analysis on the high initial retention group, ANOVAs continued to show a main effect of initial rating for both entities (heart: $F(1,52) = 31.7, p < .001, \eta_p^2 = .33$; lock: $F(1,56) = 31.2, p < .001, \eta_p^2 = .34$). This was the only significant effect for the lock. For the heart, there was also a significant interaction between condition and initial rating for the heart ($F(1,52) = 6.42, p = .01, \eta_p^2 = .07$) as well as a main effect of condition at trend level ($F(1,52) = 3.46, p = .07, \eta_p^2 = .04$). As displayed in Figure 2, the interaction between condition and initial rating was driven by children initially judging the heart as simple, who moved towards higher complexity in the mechanistic condition ($M = 1.46, SD = 0.97$) compared to the non-mechanistic condition ($M = 0.25, SD = 0.88$; Post-hoc t-test with Bonferroni adjusted alpha levels of .025 per test ($0.05/2$), $t(16.0) = 2.93, p = .009$). For children initially judging the heart as complex, there was no significant effect of condition (mechanistic: $M = -0.75, SD = 1.16$; non-mechanistic: $M = -0.44, SD = 1.04$; $t(36) = -0.85, p = .40$).

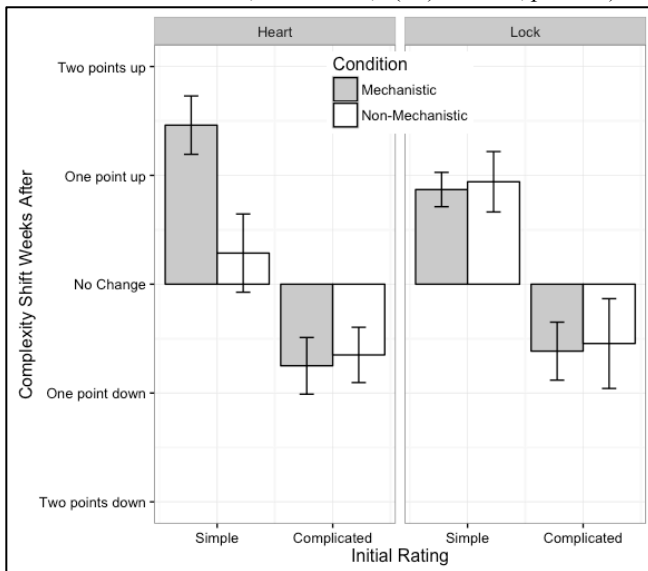


Figure 2: For the high retention group, average value of *long term shift* (y-axis) with standard errors bars in the mechanistic (grey) and non-mechanistic condition (white) as a function of initial complexity judgment (x-axis). Results for the heart and lock are presented on the left and right panels respectively.

Retention Tests Three weeks later, children’s retention scores had significantly dropped significantly by 0.20 in the non-mechanistic condition (from 0.64 to 0.44, paired t-test: $t(95) = 9.30, p < .001$) and by 0.11 in the mechanistic condition (from 0.44 to 0.33, $t(101) = 4.67, p < .001$).

When dividing our population between high versus low initial retention, the low initial retention group did not show any decay in the mechanistic condition (from 0.19 to 0.25). By contrast, the high retention group had a decay of 0.20 (from 0.57 to 0.37, $t(64) = 7.33, p < .001$). In the non-mechanistic condition, both groups showed significant

decay (low retention group had a decay of 0.17, from 0.48 to 0.31, $t(41) = 5.84, p < .001$; high retention group had a decay of 0.24, from 0.76 to 0.53, $t(53) = 7.40, p < .001$).

Discussion

Our first hypothesis H1 is well supported by the data with an absolute value of shift significantly larger in the mechanistic condition than in the non-mechanistic condition for the two entities. In short, mechanistic information influences children’s intuitions about complexity more than non-mechanistic information.

Hypothesis H2 is supported with respect to the heart: both when analyzing the full population and the high retention group, children in the mechanistic condition who initially judged the heart as simple moved toward higher complexity ratings more than children in the non-mechanistic condition. With respect to the lock, the same hypothesis was only supported by the high retention group. This pattern suggests that the influence of mechanistic information prompts more than unpredictable shifts in children’s intuitions. The influence of retention group also suggests that the quality of mechanistic exposure has a discernable impact on children’s ultimate intuitions. The finding that the low retention group slightly increased their retention score three weeks later likely means they were near floor from the start, indicating they had encoded and understood little to no mechanistic details presented to them.

For both entities, we also found significant main effects of initial rating in the following direction: children initially judging an entity as simple move toward higher complexity and children initially judging an entity as complex tend to decrease their complexity judgments. This pattern raises a question: to what extent were the shifts simple regressions to the mean? At least in the cases of the heart, a tendency towards the mean is not the only significant influence on children’s complexity judgments, even if the influence of mechanistic information works in the same direction. Indeed, mechanistic information shifted initially low complexity judgments higher than the overall tendency to regress towards the mean can explain.

Hypothesis H3 was only weakly supported in the case of the heart, with a main effect of condition at trend level. However, this modest effect fits with our hypothesis, since it is driven by children in the mechanistic condition initially judging the heart as simple who showed, three weeks later, a greater increase in their complexity judgments compared to the non-mechanistic condition. The size of this effect illustrates the challenge of trying to shift children’s long-term intuitions about the world with less than 10 minutes of instruction.

Participants’ SES, background, and attendance at a school having a strong science and engineering focus may also have diminished the hypothesized effects in two ways: first, low SES children often face increased attentional challenges in school settings (Mezzacappa, 2004; NICHD Early Child Care Research Network, 2003). These challenges may also help explain why our main hypotheses were supported more

by the high retention half of our sample. Second, the STEM focus of the school may have diminished the strength of the main effect of mechanism on the size of the shift by giving children more previous exposure to mechanism than is typical, in turn providing less room for intuitions about complexity to shift in a mere 5-10 minute span.

Conclusion

Our results have shown that even very short “mechanistic interventions” can lead to immediate and sizable changes in children’s intuitions about complexity. Crucially, when those changes happened, they were still observable three weeks later. These results suggest that teaching mechanism early in school can directly influence students’ intuitions about science and the world more broadly, even in the long term when the details are long forgotten.

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