A short-term intervention improved children’s insights into causal processes

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Abstract

Understanding of causal mechanisms has largely been ignored in past work on science learning, with studies typically assessing multiple aspects of children’s knowledge or focusing on their explanations without differentiating between accounts of factors, variables and mechanisms. Recent evidence suggests that grasp of mechanisms is in fact a crucial predictor of children’s science achievement; and that spatial-temporal ability is a key driver of this grasp, helping children to envisage the transformations involved in the continuous causal processes they encounter in science lessons. The present research tested the impact of a short-term intervention designed to promote spatial-temporal thinking with regard to one such process, sinking. Children across Years one to three from a school in a disadvantaged area (5 to 8 year-olds, six classes, N=171) were taken through a three-stage classroom exercise: Making initial predictions and observations; engaging in an imaginative game to explore the interactions between objects and water; and then testing further predictions supported by the introduction of scientific terminology. These stages modelled on a scientific investigation, targeting five key steps: (1) perception; (2) representation; (3) analysis; (4) mental imagery; and (5) use of feedback. The exercise produced substantial improvements in children’s performance, regardless of age; better observation and more accurate prediction; more coordinated representations; greater incidence of imagery and mechanism-related analysis; better sensitivity to feedback and increased use of scientific terminology. The data suggest that the ability to utilise spatial-temporal elements in causal inference is highly

malleable and that giving children space to think and talk imaginatively about mechanisms is central to their progress. At present, science lessons typically focus on the ‘what’ rather than the ‘why’, and do not actively support such thinking about causal processes.

Introduction

Recent research has examined the possible influence on science learning of the development of literacy (see e.g. Goodwin & Ahn, 2010, for a meta-analysis), numeracy (Wellington & Ireson, 2008), and spatial abilities (see e.g. Uttal et al. 2013 for a meta-analysis). We hypothesized that another dimension, spatial-temporal cognition, is central. This allows children to envisage the transformations of object states over time that are involved in causal processes and to conceptualise these as a successive chain of interactions, an ability we argue is core to their understanding of causal mechanisms (Dündar-Coecke et al., 2019, submitted a). This paper presents an initial intervention study following on from these earlier studies to explore the impact of an actual classroom exercise designed to promote the application of spatial-temporal thinking to one continuous process, sinking, among children aged 5 to 8 years, where performance was found previously to vary substantially.

Understanding mechanisms in continuous causal processes

Causal mechanisms are the generative processes by which the same effect is produced on successive occasions by the same element(s). A focus on mechanism is common in research on causal reasoning, but only with respect to distinct causal events where A causes B (e.g. one object hits another, causing it to move). There is a large literature showing that in carefully designed laboratory contexts manipulating causal events, even pre-school children have the capacity to think about mechanisms (Buchanan & Sobel, 2011; Bullock, Gelman & Baillargeon, 1982; Schlottmann, 1999; Shultz, 1982). However, evidence suggests that children – especially younger pupils – find it harder to make inferences about mechanisms in continuous causal processes of the kind encountered in much primary science, where there is no distinct initial cause, and effects occur over time. The reason for this is that these processes require causal mechanisms to be understood in a holistic fashion, combining observable and intervening unobservable factors (e.g. the competing forces of gravity and upthrust involved in objects sinking).

On our evidence, only about 20% of 5 to 11 year olds were able to explicitly report mechanisms for causal processes (Dündar-Coecke et al., 2019). This percentage was much lower for young children, and although mechanism awareness was detectible in their thinking, this varied highly depending on domain general abilities (e.g. verbal, nonverbal) and socioeconomic background. Further analyses indicated that limited awareness of mechanism has measurable negative effects on school science attainment – 7 to 10 year old pupils' mechanism inference correlated at .41 with performance on 2011 TIMMS items – (Dündar-Coecke & Tolmie, in preparation), suggesting that (1) understanding causal mechanism impacts on problem solving skills in physics/biology/chemistry, (2) children are ill-prepared for more principle/mechanism-focused science in secondary school.

The need for an intervention

We theorised that reasoning about causal mechanisms draws uniquely on spatial-temporal cognition: the ability to extract information from object states over time, organise this into an imagined sequence of dynamic mental transformations that account for observed change, and project this sequence onto past, present, and future experiences. This makes it possible to go beyond observable features of causal processes. To test this, three mini experiments were used (sinking, absorption, dissolving inspired from physics, biology, chemistry) making continuous causal processes more salient by presenting children with contrasting instances of each (Dündar-Coecke & Tolmie, submitted, b). In an interview-based design, children (study one N=107; study two N=124) had to observe/describe, hypothesise/predict, test, and infer mechanisms they witnessed. Study 1 found performance on a spatial-temporal task, measured by Piaget's (1969/2006) flow of liquid, was associated with prediction/observation and uniquely predicted which children went beyond awareness of variables to imagining mechanisms. Study 2 replicated and extended these results, finding spatial-temporal ability, as measured by two tasks – flow of liquid, and Wilkening's (1981) distance/time/velocity integration tasks – to be an even stronger predictor of, and a necessary precursor for, inference of mechanisms. Scientific vocabulary was additionally found to help children articulate their resulting insights (Dündar-Coecke & Tolmie, submitted, b).

These studies indicated that (1) understanding mechanism was effortful, involving multiple elements: changes in position and state over time need to be noted, integrated and interpreted as a connected sequence of transformations; (2) helping children to mentally slow down and segment processes into stages (e.g. imagining rate of movement) allowed them to analyse these, but constructing ideas about mechanism required them to further use spatial-temporal information to extract underlying context-specific principles (e.g. the balance between downward force/upthrust); (3) the role of spatial-temporal thinking was empirically robust for mechanism level thinking and especially influential when 'working scientifically' as specified in the English National Curriculum for science (Department for Education, 2013).

However, these data still leave it unclear what aspects of spatial-temporal cognition mediate mechanism level understanding. Further analysis of high performing children's responses suggested that there are at least five steps involved in this kind of thinking: (1) Perception; (2)

Representation; (3) Analysis; (4) Mental imagery; (5) Use of feedback. Our goal in the present research was therefore to deliberately promote these via a structured engagement, combining this with use of scientific vocabulary to promote consistent and explicit awareness of mechanism.

Previously, the impact of training in spatial-temporal thinking has been successfully demonstrated in mathematics with 5 to 12 year olds, with a completely different structure - using video games and other software - indicating no differences in outcome across grade or SES (Peterson et al., 2004; Rutherford et al., 2010). We focused here on use of physical materials to make implementation more applicable to school environments, and allow children more tangible engagement with phenomena. An in-class approach was used to facilitate natural introduction of scientific vocabulary and enlist known benefits of peer interaction for promoting explicit discussion of ideas (Tolmie et al., 2010).

Method

Participants

The sample comprised two complete classes in each of Years 1, 2 and 3 (171 children in total) at a school in a deprived area of Oxford, recruited with school and teacher consent, and ethical approval from the UCL Institute of Education Research Ethics Committee. The intervention was deployed on a whole class basis as part of normal science activity, and data were not collected from individual children.

Materials and procedure

The intervention consisted of a single extended exercise focused on objects floating and sinking in water. It lasted approximately 30 minutes, was delivered by two researchers with support from class teachers, and was structured as a scientific investigation (cf. 'working scientifically'). The exercise was based on three pillars: developing the ability to analyse *spatial-temporal information* (perception, representation, analysis); connecting these with imagery to promote *use of scientific vocabulary* (analysis, feedback); and combining factors and variables with mechanism.

Stage 1 focused on careful observation of two contrasting examples. Children were seated on the floor with their usual teacher around a low table at the front of the class, and shown a large stone and a beef tomato that were to be dropped into a tank of water placed on the table. They were asked to predict what they thought would happen, and the outcome was then demonstrated, children being asked to watch carefully and say what they saw. The stone sank rapidly, while the tomato initially dropped then floated up, this contrast highlighting the differential mediating role of the water. Children were encouraged to report any differences they noted in the nature and speed of effect. The researchers made sure all the key features of the outcomes were explicitly identified and understood by the children, to help them mentally replay these and begin to organise and analyse them.

Stage 2 was an imaginative game, aimed at helping children reflect on and further analyse the observations made at Stage 1, thinking in particular about the invisible mechanisms involved: the mediating role of the water, the relationship between the objects falling and the water pushing up, and the consequences of this over time. In threes, they were assigned to be water, stone, and tomato, and asked to play out the sequence of interaction between these ("what does the water do to the stone?" and so on). After approximately five minutes, each threesome was then asked to relate their ideas, 'water' reporting what it did to the objects, the objects why they behaved differently. Thoughts were collated in writing by one of the researchers, using a flip chart adjacent to the table, and compared without focusing on accuracy, since the principal objective was simply to promote this type of thinking.

Stage 3 was designed to stimulate further spatial-temporal analysis by extending it to related instances. First, each threesome was given one of a set of new objects varying in sinking rate/floating (e.g. peeled and unpeeled orange, ball of playdough, button, piece of dense wood, a metal dish, a plastic stick), and asked to make use of their ideas thus far to decide whether it would sink fast/slow or float (prediction). They were then given the opportunity to drop their object in the water, stating their prediction first (testing); and asked to explain what happened with the help of the other children, again drawing on ideas from Stage 2 (conclusion). A final pair of novel objects was then presented (a coin and a large piece of pine), for the children to make predictions and justify these in terms of their ideas about mechanisms. During this discussion, scientific vocabulary was introduced naturally by the researchers, by displaying and referring to an A0-sized diagram labelling relevant variables and forces (see Figure 1), and engaging children in a simple activity ("jump up high, what pulls you down?"), to help them explicitly capture mechanisms. At both points, children's ideas were again recorded on the flip chart.

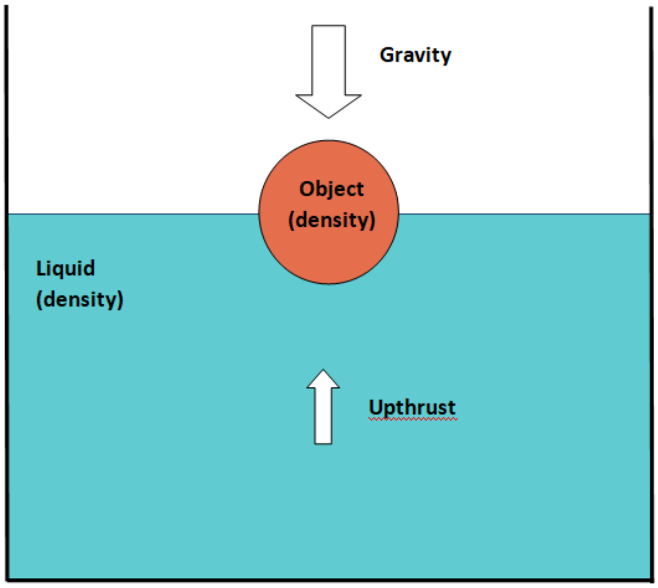

Figure 1. Diagram used in Step 3 of the intervention exercise to introduce scientific vocabulary.

Results

Table 1 shows the accuracy of children’s initial and final predictions, and the record of their ideas during Stages 2 and 3 of the intervention exercise, broken down by class. They exhibited good engagement with the activity, and greater accuracy of predicted outcomes, improving from 41.5% at first – approximately chance level – to 75.5% at the end, though some children declined to make predictions at the last stage, suggesting they had shifted to greater uncertainty rather than definite ideas.

Children also made considerable use of mechanism-related explanations, especially following the imaginative game where there were 15 instances (e.g. “water pushed the rock and tomato, but tomato came back because it was not heavy” [Year 1, Class 1]; “water pulled and pushed tomato” [Year 2, Class 1]; “Water pushed the tomato down then pushed it up” [Year 3, Class 2]), and 22 overall. They also exhibited greater use of scientific terms after these had been introduced, with 13 instances of these (“gravity pulls it down” [Year 1, Class 1]; “water is pushing less dense things up” [Year 2, Class 1]; “things more denser than water

Table 1. Record of children's predictions and ideas in each class (mechanism explanations in bold; use of scientific vocabulary in italics).

Class	Prediction before initial demonstration	Ideas after imaginative game	Ideas after predicting and testing	Ideas after introduction of scientific vocabulary	Prediction for final items
Year 1 Class 1	12 right 15 wrong	**Stone is heavier than the water, that's the reason it's going down** Tomato is soft and small, not big and heavy **Water cannot hold up stone** It turns orange and looks bigger in the water **Water pushed the rock and tomato but tomato came back because it was not heavy**	They look the same but orange was heavier than the peeled one Peeled orange was smaller **Water can push up some items** Water gets into the peeled orange, it makes it sink There is not much playdough inside it slowly sinks **The water thinks that heavy things cannot be carried**	*Coin is much denser* Coin looks little but it sank faster Penny is made of metal Penny is heavy and strong, wood is not Heavy and strong things sink *Gravity pulls it down*	17 right 3 wrong
Year 1 Class 2	12 right 15 wrong	Tomato is lighter **Water can carry tomato because it's light** **Stone was heavy and big, water pushed it up** **Stone is heavier than water** **Water pulls tomato down and push it up again** **Water is not stronger than stone**	Orange skin surrounds it All the items are different some big ones don't sink **The water pushed tomato up** Button has holes in it, it sank	Penny made up metal, the other is wood Coin is heavier *Coin has more gravity*	9 right 7 wrong
Year 2 Class 1	12 right 15 wrong	I felt warm and wet in the water I couldn't breath under water I felt heavy (stone) I drunk the water **I was fighting with water, wanted to go to surface** **Stone is heavy water can't keep it up** Stone was heavier than tomato **Water pulled and pushed tomato** Tomato likes water, coming back to surface	The weight of the items is important Squishy, softer things are lighter than stone Harder things sink Size of the item do something about sinking	*Penny is more denser, wood is less dense* *Less dense items float* ***Water is pushing less dense things up*** *Metal is more denser than other items*	19 right 8 wrong
Year 2 Class	8 right 23 wrong	Stone is heavy going down fast Tomato was not as heavy as the	*Gravity pulls heavy things down* Things on the top are not heavy	*Gravity pulled the stone down* **Water pushed up tomato**	19 right 5 wrong

2		stone **The water pushed up the tomato**	Little things sink Things have round shape go up		
Year 3 Class 1	15 right 15 wrong	**Stone is heavier than water.** Both items have nearly same weight Tomato has less weight Liquid has more air *Gravity pulls it down* **Water pushing it back**	Shape and air is important The amount of air is important in sinking Air wants to rise up Some things are squishy some things are not, squishy things float Hard, melted opposite squishy, Things have protection (e.g. orange) float	*Gravity pushes objects down* *Some items has more gravity* ***Things more denser than water sink***	22 right 1 wrong
Year 3 Class 2	12 right 17 wrong	Keeping fresh Water surrounding me Tomato is the lightest All the items different inside I felt I was stuck in the water (stone) Stone is heavy Water was pulling me down Texture is different **Water pushed the tomato down then pushed it up** I was happy when I came back	Air is important Some things have oxygen inside Some things have protection (e.g. orange) Protection keeps water outside Air inside makes things float	***Upthrust will make things float*** Heavy things go down *More dense things sink* *Less dense things float*	19 right 10 wrong

sink" [Year 3, Class 1]). Importantly, there were also instances of the combination of mechanism explanations and scientific terminology at this point. There was little evident difference between classes in either mechanism explanations or use of scientific terms, regardless of age, though older children did exhibit some tendency to couch explanations in more generic terms (e.g. "coin is much denser" [Year 1 Class 1] vs "more dense things sink" [Year 3, Class 2]).

Discussion

There are good grounds for concluding that the intervention had widespread immediate effects on children's understanding. Given their socioeconomic background – the majority of children came from low SES families – this effect was promising. Examining the success rate in terms of the five steps outlined earlier, the results demonstrated:

Improvement in perception. Previous research (Dündar-Coecke et al., 2019) with a mixed SES sample showed that some children (as many as 69% in Year 1) did not actually see a stone and a grape sinking at different rates, or a piece of tissue paper soaking up water more/faster than a piece of blotting paper, and so on. This corresponded to a lack of ability to extract information from objects and their states over time. The intervention aimed to improve children's observation skills, and their awareness of items behaving differently increased substantially, as is evident from the shift in the accuracy of their predictions.

Employing of representations. Children's responses required them to employ their representations of the experiments they witnessed, as their watching of the demonstrations was followed by answering questions about these. This corresponds to abstraction of causal relations linking object features to effects, including integration and coordination of operative variables, such as weight and size, and weight relative to the water. The intervention increased these and process-based explanations, since all children had an active role in the game, and they needed to play/explain their role.

Improvement of analysis. Although children in this sample came from disadvantaged backgrounds, they performed better than the more advantaged sample employed in our previous research: here, nearly 13% of children proposed mechanisms for sinking, against fewer than 6% of children in the same age range in the earlier study (Dündar-Coecke, Tolmie, Schlottmann, submitted, a).

Imagery. References to mechanism appeared immediately following the game section of the intervention. On the basis of this initial trial, we hypothesise that giving children space to think and talk imaginatively about mechanisms is fundamental to its benefits, and should be central to its further evaluation. The ability to analyze spatial-temporal information appears to be highly malleable, and children can become aware of these dimensions and learn how to use them in their causal analysis in a short period of time. However, the imaginative component of the intervention may be especially crucial in carrying children from extraction, representation and analysis of spatial-temporal information to actual imaging of causal mechanisms that dynamically tie these elements together – the key step that the majority of primary age children seem unable to make within current science teaching (Dündar-Coecke, Tolmie, Schlottmann, submitted, a).

Feedback. The imaginative game at Stage 2 and the introduction of scientific vocabulary at Stage 3 had their intended critical effects. Not only did references to mechanism first appear following the game, these were sustained through Stage 3. Similarly, there were very few instances of use of scientific terminology – and none of ‘density’ – prior to its introduction in Stage 3, but following this it became notably more common as a means of expressing the ideas that had emerged earlier (e.g. “heavier than the water”) in more succinct fashion. Teachers expressed considerable surprise at some of the things that children in their classes said, noting that they had never heard them make such statements previously. They also reported subsequent re-use of these same ideas by children in science classes some days later.

Taken overall then, the intervention produced very positive results. Nevertheless, it remains to be established whether this training has long term impacts and whether children can generalize their awareness over different causal events. What is needed is a more extended trial using a set of similar exercises, focused on specific yet linked causal mechanisms, to promote familiarity with imaginative spatial-temporal thinking in consistent fashion, and encourage accumulation and re-use of scientific vocabulary. The objective would be to make a) horizontal connections, promoting consistency of approach, spreading spatial-temporal thinking across topics, and familiarising children with the employment of the three pillars, as well as the importance of visible and invisible processes in their causal thinking; and b) vertical connections, preparing children to take this way of thinking forward into later curriculum topics – creating a habit of thought benefiting later learning in science for all children.

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