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Developing multivariable thinkers

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ABSTRACT

Scientific thinking skills figure centrally in new science curriculum standards. We identify as a broad and critical dimension of skilled scientific thinking one that has received little previous attention – the conceptualization of multiple factors jointly affecting an outcome. In a preliminary study, we established that even lay adults show less than optimal competency in this regard. In two intervention studies, we undertook to foster this competency in middle-school students. Although performance levels were initially low, students' skills and understanding were amenable to development as outcomes of both a multi-year and a less extended intervention. We consider implications regarding what needs to develop in the development of scientific thinking and the mechanisms involved.

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Central to scientific thinking is representation of causal relations (Perkins & Grotzer, 2005; Sloman, 2005). In both the real world and in formal scientific models, multiple causes act additively and interactively on an outcome. Scientists arguably subscribe to certain generic meta-knowledge regarding such causal models. Notably, (a) a cause is expected to be consistent in its effect under constant antecedent conditions; (b) causes are expected to be cumulative in their effects, additively or interactively, i.e., multiple causes may contribute to an outcome; and (c) alternative causes must be evaluated and possibly excluded before causality can be inferred. We can regard this meta-knowledge as part of a generic mental model of causality that scientists share (distinguished from their more detailed models of specific causal phenomena). It is also reflected in the statistical models they rely on, notably the analysis of variance (ANOVA). In the work presented here, we ask to what extent this generic model

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is shared by children and adult non-scientists, and, to the extent it is not, what kinds of educational interventions might be effective in developing it.

Children are born into a world of multiple interacting phenomena. Over the course of their lives, they will construct and revise mental models of how the multitude of variables they encounter connect to one another, most often as causes and effects. In early childhood, the process of constructing and revising these mental models in the face of new experience occurs at an implicit level the child is largely unaware of (Bullock, 1985; Kuhn, 2012). By the second decade of life, the more explicit, consciously controlled coordination of claims and evidence can be seen to emerge, in what has come to be regarded as the core of scientific thinking (for review see Kuhn, 2011; Lehrer & Schauble, 2006; Sodian & Bullock, 2008; Zimmerman, 2000, 2007). To achieve this control, children must become "data readers" (Kuhn & Katz, 2009; Lombrozo, 2006; Williams, Lombrozo, & Rehder, 2010, 2013); that is, they must mentally represent an existing understanding as an entity in its own right (thinking "about" rather than only "with" a theory), encode and represent as a distinct entity the new information encountered, and consider its bearing on the existing understanding (that which is already taken to be true). Reconciliation of the two ideally follows (Koslowski, Marasia, Chelenza, & Dublin, 2008; McElhaney & Linn, 2011), but firmly distinguishing them is a first and essential step.

In the simplest case, a causal model involves only two variables, typically an antecedent (A) variable and outcome (O) variable, with A construed as the cause of O. Information as minimal as a single instance of the co-occurrence of A and O commonly is taken as evidence for a causal claim (Fernbach, Darlow, & Sloman, 2010; Fernbach, Macris, & Sobel, 2012; Koerber, Sodian, Thoermer, & Nett, 2005; Kuhn, 2012; Sloman, 2005). Except in highly controlled laboratory investigations, however, this simplest case is a rare one and represents a very narrow portrayal of the complexity children and adults encounter in their own experience. Almost always, multiple variables are present as part of any situation and may be seen as candidate As or Os in relation to one another. It is the explicit reasoning about such situations that is our focus here.

Management of multiple variables has in fact figured prominently in research on the development of scientific thinking. Hence it is important for us to emphasize that in the present work we are examining the coordination of multiple variables in a sense distinctly different from the one that has become traditional in both science education and in research on scientific thinking. The traditional focus has been on acquisition of the control-of-variables (COV) strategy, in which all variables except a focal one must be held constant in order to assess the effect of the focal variable on an outcome (for review see Klahr, Zimmerman, & Jirout, 2011; Kuhn, 2011; Zimmerman, 2000, 2007). The effect is thus to "neutralize" (Inhelder & Piaget, 1958) all variables but one by removing them from consideration. Mastering the COV strategy has become a standard feature of the science curriculum across multiple grades, beginning with what some elementary teachers label for their students as the "you-change-it" and the "you-measure-it" variables.

This focus, we suspect, may work against mastering the coordination of multiple effects that we study here, as required in the prototypical context in which two or more causes simultaneously affect an outcome. In these cases, their combined effects must be identified and coordinated.

The present work follows from research reported by Kuhn and colleagues (Kuhn, 2007; Kuhn & Pease, 2008; Kuhn, Pease, & Wirkala, 2009), in which urban public school students participated in an extended intervention during their 6th and 7th grade years, designed to promote development of scientific thinking skills through dense engagement with activities requiring them. We found that students by the middle of the second intervention year showed solid evidence of consistent (although not always perfect) use of a COV strategy in designing their own scientific investigations in multivariable virtual environments. At the same time, however, they continued to exhibit considerable difficulty with respect to the competency we have identified here – integrating the individual factors that their investigations identified as operative into a portrayal of the joint influence of these factors on the outcomes of interest. Specifically, in making outcome predictions for new multivariable cases, they violated the first two norms we identified earlier. They did not take into consideration the effects of all of the variables they had earlier identified as causal, a single variable typically sufficing as the basis for the prediction, and b) they did not show consistency in which variable(s) they implicated as causal, shifting from one to another over successive cases.

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