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Factor Analysis of Drawings: Application to college student models of the greenhouse effect

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Exploratory factor analysis was used to identify models underlying drawings of the greenhouse effect made by over 200 entering university freshmen. Initial content analysis allowed deconstruction of drawings into salient features, with grouping of these features via factor analysis. A resulting 4-factor solution explains 62% of the data variance, suggesting that 4 archetype models of the greenhouse effect dominate thinking within this population. Factor scores, indicating the extent to which each student's drawing aligned with representative models, were compared to performance on conceptual understanding and attitudes measures, demographics, and non-cognitive features of drawings. Student drawings were also compared to drawings made by scientists to ascertain the extent to which models reflect more sophisticated and accurate models. Results indicate that student and scientist drawings share some similarities, most notably the presence of some features of the most sophisticated non-scientific model held among the study population. Prior knowledge, prior attitudes, gender, and non-cognitive components are also predictive of an individual student's model. This work presents a new technique for analyzing drawings, with general implications for the use of drawings in investigating student conceptions.

Keywords: *Alternative conceptions; Climate change; Factor analysis; Drawings; University*

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1. Introduction

The field of inquiry that investigates people's non-scientific conceptions of the natural world (termed 'alternative conceptions' herein) expands across almost all disciplines, ages, places of origin, and theoretical perspectives. Alternative conceptions research provides a venue for understanding how people view the world. Instruction can be powerfully transformed in response to student thinking, with attendant measurement of student learning relative to incoming ideas.

Researchers use a wide variety of methods to investigate alternative conceptions. Studies investigating drawings in particular are becoming increasingly common, particularly as faculty in higher education have become more interested in student misconceptions. By examining these visual representations of the learner's internal model, educators have identified misconceptions in many scientific domains, for examples: environmental science (Bowker, 2007; Shepardson, Choi, Niyogi, & Charusombat, 2011), biology (Fischer & Young, 2007; Myers, Saunders, & Garrett, 2003), chemistry (Harrison & Treagust, 1996; Smith & Metz, 1996), and geoscience (e.g. Ross, Duggan-Haas, & Allmon, 2013; Smith & Bermea, 2012).

1.1. *Alternative Conceptions of Climate Change*

The present study focuses on student drawings of the greenhouse effect, warranting a brief overview of studies that have investigated conceptions of climate change. The term 'greenhouse effect' can itself cause confusion among students, as can the more general concepts of 'climate change' and 'global warming' (e.g. Shepardson et al., 2011). Similarly, the general public responds differently to survey questions when 'climate change' and 'global warming' are interchanged; in general, climate change evokes less concern than global warming (Whitmarsh, 2009).

More broadly, climate change and related constructs are poorly understood by most groups, including the general public (Weber & Stern, 2011; Whitmarsh, 2009), K-12 (Sweeney & Sterman, 2007) and college students (Lombardi & Sinatra, 2012), teachers (Papadimitriou, 2004), and meteorologists (Maibach, Witte, & Wilson, 2011). For example, secondary students internationally often incorrectly draw causal conclusions between climate change and unrelated phenomena such as ozone depletion (Liarakou, Athanasiadis, & Gavrilakis, 2011; Punter, Ochando-Pardo, & Garcia, 2010). Similar inaccurate causal relationships have been observed in students of all ages, from elementary through college (Karpudewan, Roth, & Abdullah, 2014; Lambert, Lindgren, & Bleicher, 2011). Important for this study, student drawings of the greenhouse effect illustrate a prevalence of specific alternative conceptions (e.g. Shepardson Niyogi, Choi, & Charusombat, 2009) as well as models that appear to underlie student ideas (e.g. Shepardson et al., 2011).

Suggestions for improving climate literacy have been proposed and implemented across many populations and over many years (Sterman, 2011; Svihla & Linn, 2012), most of which focus on uncovering and utilizing existing alternative conceptions as the basis for instructional interventions (McCaffrey & Buhr, 2008;

Pruneau et al., 2001). Other scholars suggest that portraying climate change as a concrete and immediate risk (Ungar, 2000), disaster narratives as pathways to decision-making (Lowe et al., 2006), and inclusion of values and affect related to climate change (Leiserowitz, 2006) can all encourage learning. Despite the effort to communicate key concepts about climate change and encourage action, the public maintains misconceptions (Weber & Stern, 2011) and is generally slow to act (Ungar, 2000). This suggests a need for more research into the effectiveness of climate change communication (Moser, 2010), as well as the complex factors that influence climate change understanding (Weber & Stern, 2011). Finally, several variables are known to correlate with understanding of scientific phenomena in general, or climate change understanding in particular. Gender and ethnicity gaps exist on assessments of general scientific understanding, often with male or non-minorities scoring higher on measures than females or minorities (e.g. Bacharach, Baumeister, & Furr, 2003).

2. Using Drawings to Investigate Alternative Conceptions

2.1. *The Visual Study of Conceptions*

Visual and verbal representations of phenomena convey different information. In science, researchers generally agree that coupled visual and verbal representations are most effective for conveying information (Carney & Levin, 2002; Mayer, 1989; Trumbo, 1999). For example, Cheng and Gilbert (2009) recommend that drawing be used as a means of corroborating and detailing student understanding. The cognitive tasks involved in learner-generated drawings can include recalling verbal and visual information, selecting which information to use, and integrating those elements into a drawing (Van Meter & Garner, 2005). As such, students' visual representations of phenomena can provide rich understanding of student alternative conceptions and underlying mental models (Ainsworth, Prain, & Tytler, 2011). We report here on methods used to analyze student drawings, specifically about scientific phenomena.

2.2. *Analysis of Drawings*

Several techniques have been used previously to analyze student drawings in science (Table 1). The most fundamental approach is indexing, in which researchers analyze drawings for the presence of salient features. These features are reported in ways that document the presence and prevalence of features across the research sample (e.g. Alerby, 2000; Harrison & Treagust, 1996; Myers et al., 2003). For example, Shepardson et al. (2009) present evidence that some grade 7 students, 19% in their case, drew a literal greenhouse when asked to draw a model of the greenhouse effect, while another 9% incorporated ozone or ozone depletion into their models. While identification of common themes in drawings can be seen as the end result of research, indexing also underlies other approaches to grouping drawings.

Understanding the relationship of features to each other allows deeper recognition of how a drawing represents complex phenomena. Analysis of feature relationships can

Table 1. Comparison of drawing analysis approaches

	Image features used for analysis	Coding	Statistical analysis	Speed	Largest source of error
Computer grouping	Predefined by researcher; limited in complexity	Computer	% containing feature or relationship	Fast	Computer
Indexing	Predefined or emergent	Human	% containing feature or relationship	Slow	Human
Manual grouping	Predefined or emergent	Human	% categorized within a group	Slow	Human
Factor grouping	Predefined or emergent	Human	Factor score	Medium	Computer and/or human

provide an understanding of the underlying mental models held by students, often achieved through a thematic content analysis via visual inspection. For example, Shepardson et al. (2011) extended their earlier analysis of drawings to visually identify overarching mental models represented by students. This offers more nuanced understanding of the processes that students bring to mind when considering the greenhouse effect. Much like the indexing analysis, Shepardson et al., (2011) identified both a physical greenhouse and an ozone depletion model among their drawings. Although interesting, inherent limitations to human cognition suggest that some underlying patterns may not be observable through inspection alone.

Pattern analysis of drawings relying on computer-based approaches (e.g. Brown, Henderson, & Armstrong, 1987) is rarely used by the communities investigating student conceptual understanding although some use of symbology-based approaches have been attempted. For example, CogSketch (Forbus, Usher, Lovett, Lockwood, & Wetzel, 2011) analyzes qualitative symbology in drawings to allow analysis of cognitive processes underlying drawing generation. The use of computers to automate the analysis and grouping process provides a level of sophistication in the analysis of drawings that is impossible when visual inspection is used alone.

2.3. *Present Study*

This study capitalizes on the strengths of computer-based analysis of drawings (e.g. Brown et al., 1987; Forbus et al., 2011), and considers the extent to which factor analysis can be used to identify underlying representative models of student drawings. Specifically, we addressed the research question: *Can deconstruction of drawings into salient elements and application of factor analysis reveal underlying representative conceptual models?* As a null hypothesis this could be stated as, 'Factor analysis will not reveal relationships between conceptual drawing features.' We applied this hypothesis to student drawings of the greenhouse effect for three reasons. First, climate change and underlying concepts like the greenhouse effect are processes of particular importance for general scientific literacy. Second, the greenhouse effect lends itself to visual representation and is often portrayed visually in texts and media. Finally, other researchers (e.g. Shepardson et al., 2011) have analyzed greenhouse effect drawings using the visual inspection approach, providing an opportunity for us to compare our findings independently.

Categorization of drawings implies an underlying structure that should emerge from a factor analysis of salient features. The absence of such a structure would imply that groupings of drawings are based on variables other than salient features, such as individual rater bias. A subordinate research question considers the extent to which existing conceptions, attitudes, and demographic variables relate to the model drawn. Based on prior work, we hypothesize that individuals with higher conceptual understanding and more positive attitudes toward science will draw more sophisticated models. We also explore the extent to which gender, ethnicity, and non-cognitive (i.e. artistic) features of drawings are related to drawing categories and the extent to which student drawings are similar to, or dissimilar from, scientists' drawings.

3. Methods

3.1. *Participants*

Entering college freshmen attending an orientation seminar completed a survey measuring understanding of and attitudes toward science; seven faculty attending an on-campus meeting to discuss climate change education also completed surveys. We report on an analysis of 225 student surveys and 7 scientists' surveys. The student population was 47% male, had a median age of 18 years, with an average age of 17.8 ± 0.5 years, self-identified as 75% Caucasian with the remainder Asian, African-American, Hispanic, or biracial, and originated from two US Midwestern states.

Data from a small group of scientists were also collected to ascertain ideal responses as well as reasonable expectations for students. The expert group consisted of four faculty, one postdoctoral scholar, and two graduate students. Specializations for these experts included physics (both graduate students), biology (two faculty), ecology (one faculty and one postdoctoral scholar), and science education (one faculty); all but one of these participants teach or develop entry-level climate change curricula. Experts completed a survey containing an open-ended question with an explicit prompt for a drawing of the greenhouse effect, the six multiple-choice climate change conceptions questions, and demographic questions. Scientists were five women and two men, identified as Caucasian, and ranged in age from 28 to 53 years.

3.2. *Materials*

Participants completed a survey containing multiple-choice, Likert, and open-ended questions. Thirteen multiple-choice questions were taken from the Geoscience

Concept Inventory—Expanded (Libarkin, Ward, Anderson, Kortemeyer, & Raeburn, 2011 and references therein), probing climate change and general science understanding. Climate change questions asked students to reflect on concepts like the greenhouse effect, asking, for example, 'If human civilization had never developed on Earth, would there be a greenhouse effect?' General science questions probed broader understanding about concepts such as density, cell function, and radioactivity. Eight Likert questions measured simple understanding of the nature of science and attitudes toward learning science in four-item simplifications of validated scales (Libarkin, 2001). For example, nature of science was probed with 'Scientific beliefs do not change over time' and attitudes toward learning science is reflected in responses to, 'I would like to learn more about science.' An open-ended question prompting a drawing of the greenhouse effect ('Draw a picture that explains "the greenhouse effect" on Earth. Use labels to explain your diagram') was followed by simple demographic questions. We report on a unique analysis of drawings of the greenhouse effect, relationships between student drawings and other variables, and comparison with scientists' drawings.

3.3. *Survey Procedure*

Student participants completed multiple-choice, Likert-type, and open-response questions, in that order, midway through an orientation session for incoming college freshmen. Scientists completed the survey at the end of a science education seminar. The survey was administered by one of the co-authors. Participants were provided with a brief consent paragraph, and given the option of opting out of the data collection. Participants took between 10 and 20 minutes to complete the survey.

3.4. *Analytical Procedure*

Greenhouse effect drawings were coded for salient, emergent characteristics of participants' greenhouse effect models through thematic content analysis (Patton, 2002). Only those characteristics related to conceptual understanding of the greenhouse effect were considered to be relevant to uncovering internal mental modes. In addition to emergent codes, codes relevant to the scientific model were included in the coding analysis to allow identification of drawings containing aspects of scientific models. Finally, three non-cognitive variables of potential interest—drawing orientation, use of arrows, and realism—were observed during the coding process and were added as potential variables of interest. Two authors coded 125 drawings together, adding and revising codes as the process progressed. Once the coding schema was solidified, each rater coded half of the remaining drawings independently for a total of 225 coded drawings. Finally, the third author coded a subset of 30 surveys to establish interrater reliability. An intraclass correlation was determined separately for both the cognitive and non-cognitive drawing variables, with a value of 1.0 representing a perfect intraclass correlation. The calculated average intraclass correlations were 0.93 (min = 0.91 and max = 0.94) and 0.93 (min = 0.91 and max = 0.95) for 14 cognitive variables and 3 non-cognitive variables, respectively. These results indicate strong agreement across raters.

Exploratory factor analysis was performed to identify common relationships between drawing codes and emergent representative models, with natural groupings of codes emerging through this analysis. Although rotation is the norm in factor analysis, an unrotated solution was deemed appropriate in this case. Rotation is normally conducted to produce the 'simplest' solution, one in which items load on one and only one factor. Here, we expect different models to contain identical components, such as the Sun. The unrotated factor solution provides for codes that appear in multiple models, whereas the rotated factor solution would have forced individual codes to align primarily with a single factor. Factor analysis was chosen over cluster analysis as factor analysis allows for negative factor loadings and calculation of factor scores. In the context of drawings, negative loadings would identify features highly unlikely to occur in tandem with a specific model. Factor analysis also generates individual model scores for each drawing, offering insight into the extent to which an individual drawing aligns with one or multiple representative models.

4. Results

All participants in the orientation session completed some component of the survey. Of the 225 participants, 224 completed the multiple-choice and Likert scale questions, and 220 completed all demographic questions. Seventeen of the 225 participants did not complete the drawing prompt, or responded, 'I don't know'—this means that 208 drawings were ultimately analyzed. Analysis of responses for respondent and non-respondent groups indicates that groups are nearly identical demographically, as well as in terms of attitudes, perceptions, and understanding.

4.1. Multiple-Choice and Likert Scale Items

Participants ($n = 225$) demonstrated good attitudes toward science, strong understanding of the nature of science, and moderate conceptual understanding. On a scale of 1–4, where 1 indicates negative attitude and 4 indicates positive attitude, participants averaged 3.0 ± 0.6 in their attitudes toward science (equivalent to 'good' attitudes). Participants averaged 3.6 ± 0.4 in the understanding of the nature of science, equivalent to 'good-strong' understanding, where 1 implies weak understanding and 4 implies strong understanding. Two conceptual understanding measures of climate change and general science indicate about 50% understanding of basic science among the sample, producing average scores of 2.9 ± 1.3 (out of 6) and 3.3 ± 1.6 (out of 7), respectively.

4.2. *Drawing Analysis*

The coding process resulted in 14 cognitive characteristics of drawings, as well as non-cognitive elements: whether or not the drawing was intended to be viewed left-to-right,

right-to-left, or was ambiguous, the level of abstraction or realism in the drawing, and the purpose of arrows within the drawings. An example drawing, containing six cognitive codes and three non-cognitive codes, is provided to illustrate this coding process for both cognitive and non-cognitive elements (Figure 1).

We investigated the factorability of the 14 cognitive drawing codes through exploratory factor analysis. The data set met the minimum conditions necessary for factor analysis, with a final sample size of 208 and at least 14 cases per code. Criteria demonstrating factorability were also considered. First, the majority of the codes correlated with at least one other item at a level over 0.3, indicating that a factor structure could be expected to emerge. The Kaiser–Meyer–Olkin measure of sampling adequacy was 0.739, above the 0.6 value recommended for factor analysis. Finally, Bartlett's test of sphericity was significant ($\chi^2(91) = 1059$, $p < .001$). Communalities for all codes were above 0.3, with most over 0.5, indicating shared variance with other codes (Table 2). Given these data, exploratory factor analysis was performed on all 14 codes.

Four factors emerged from the exploratory analysis based on eigenvalues ≥1.0, while standard scree plot analysis suggested the presence of three factors. Closer investigation of factor loadings indicated that all four factors contained at least three items which loaded at >0.32 (Tabachnick & Fidell, 2001; Table 2). This coupled with the alignment of the observed factor structure with actual student drawings prompted us to maintain four factors. In addition, one set of codes (7a,b) consisted of mutually exclusive codes; the presence of the 'a' code requires the absence of the 'b' code, and vice versa. The observed factor structure accommodated this mutual exclusiveness. The first of these 4 factors explains 27.9% of the data variance, the second factor 14.9%, the third 11.9%, and the fourth 7.4%. This 4-factor solution thus explains 62% of the data variance across the 14 codes. Negative loadings are interpreted as codes that are strongly unrelated to a specific representative model, and thus highly unlikely to occur in a drawing aligned with that model. That is, while the presence of codes with positive loadings will increase the model score of an individual drawing, the presence of negatively loaded codes will decrease the model score.

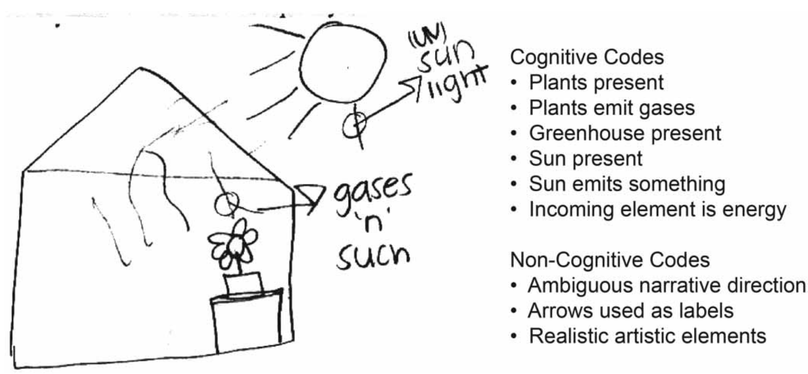

Figure 1. Example student drawing and related coding

Table 2. Factor loadings and communalities based on a principle components analysis without rotation for 14 coded drawing characteristics (N = 208)

Drawing characteristics	A	B	C	D	Communalities
1. Plants present	−.516	.697			.784
2. Plants emit gases	−.406	.707			.735
3. Greenhouse present	−.370	.574			.504
4. Sun present	.564	.350	.465		.661
5. Sun emits something	.648	.424	.465		.816
6. Incoming element is energy	.517		.346	.350	.546
7a. Incoming element passes unabsorbed through atmosphere	.837				.793
7b. Incoming element is absorbed/trapped by atmosphere			.785		.649
8. Element reflected unchanged by surface and/or atmosphere	.825				.789
9. Barrier 'stops' something from escaping	.664		−.370		.582
10. Something escapes to space	.497				.345
11. Gas layer present	.492				.338
12. Ozone or hole in atmosphere present		−.474	.355	.457	.582
13. Pollution, fossil fuels, or pollution agent (car/ factory) present		−.372		.639	.563

Notes: Factor loadings <0.32 are suppressed. Negative factor loadings (in gray) indicate that a particular drawing characteristic is highly unlikely to be present within a drawing belonging to a model class, reducing the model score for any drawing containing that characteristic.

Standard models derive from the factor structure represented in Table 1 (Figure 2). These four models are representative; while no single participant drawing will look exactly like any of these models, all drawings can be classified based on their similarity to each model. For example, the drawing in Figure 1 received factor scores of −1.11, 2.77, 0.41, and 0.45 for Models A, B, C, and D, respectively. These scores accurately depict the fact that the drawing contains the five elements aligned with Model B, three of which are negatively aligned with Model A, and contains one element also present in Models C and D. We also include a fifth model (Figure 3) representing the most salient features of the scientific model of the greenhouse effect for comparison. We note that this model was not present in the student participant sample, and was only represented by one of the scientists (Figure 3).

Cronbach's alpha was calculated for each model to consider internal consistency. Since the intent of this work was to develop standardized models that represent the dominant classes of drawings, we only considered the positively loading elements in calculating Cronbach's alpha—that is, those codes that are present in a given model. Model A (eight items; Table 2; Figure 2(A)) produced a Cronbach's of 0.81. Models B (5 items; Table 2; Figure 2(B)) and C (5 items; Table 2; Figure 2 (C)) produced less robust, but still acceptable, values of 0.53 and 0.56, respectively. Model D (3 items; Table 2; Figure 2(D)) showed low internal consistency, producing a Cronbach's of 0.11, as expected given that this model contains only 3 codes and

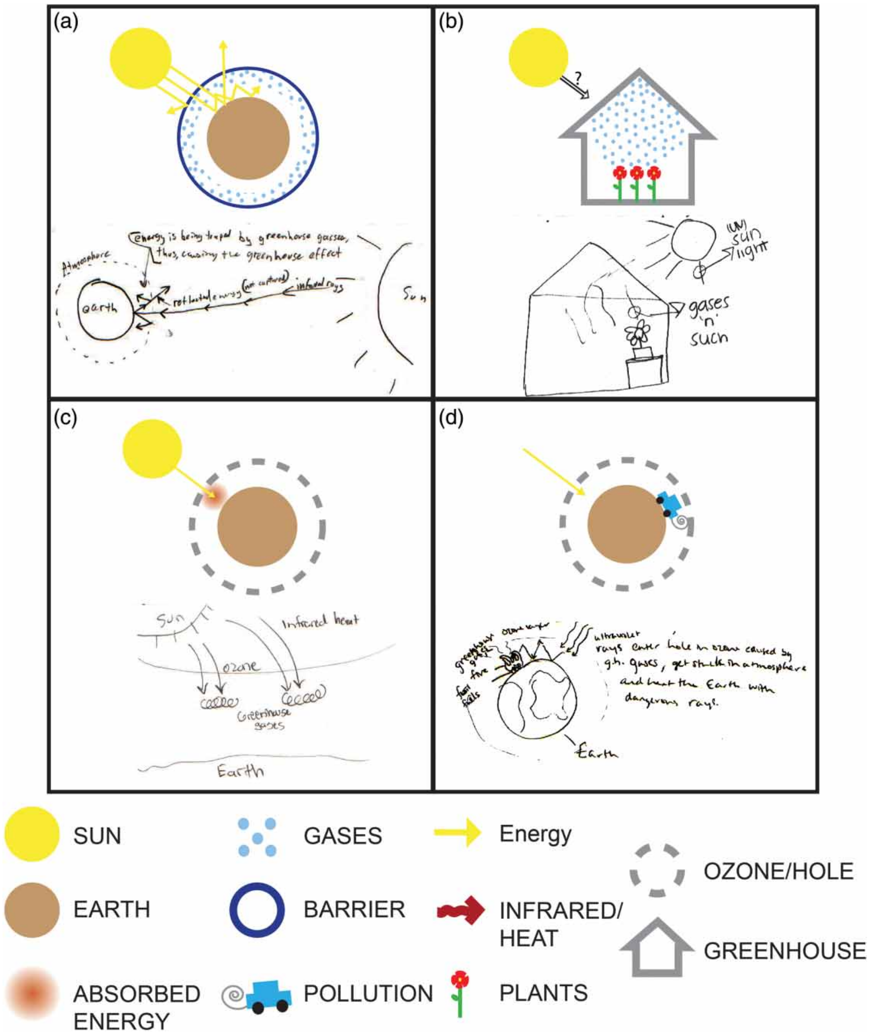

Figure 2. Four models emerging from the factor analysis of drawing characteristics, coupled with representative drawings. Letters indicate model as in Table 2

explains only 7.4% of the variance overall. We chose to maintain Model D among our representative models, although the low internal consistency ruled out further statistical analysis of Model D relative to other variables.

Factor scores, based on the regression approach, for Models A, B, and C were calculated for each drawing. These scores measure the extent to which a drawing could be classified as belonging to one or more model classes. While many individual drawings can be placed predominantly within one model class, a few drawings belong to multiple classes. Ultimately, the size and direction of the factor score represents the strength of agreement between the participant's unique drawing and the representative model. Exemplar drawings illustrate the extent to which some drawings aligned almost perfectly with the models derived from the factor structure (Figure 2).

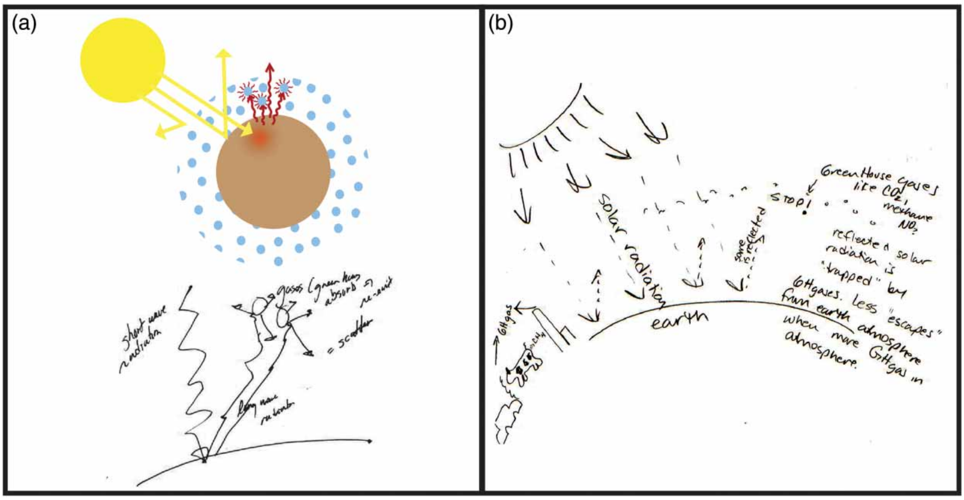

Figure 3. (a) Ideal model paired with accurate scientist's drawing of the greenhouse effect. Note that this drawing aligns closely with the ideal model. (b) Typical scientist drawing. Note that this aligns with Model A as depicted by students, with the addition of explicit transformation of energy at the Earth's surface. Key as in Figure 2

The drawings with high scores within the Model A classification contain a Sun emitting energy that penetrates the Earth's atmosphere, bounces, encounters a layer of gases in the atmosphere, is stopped from exiting the atmosphere by a barrier, and proceeds to bounce between the Earth's surface and the barrier (Figure 2(A)). The layer of gases and the trapping barrier are not always the same, hence our distinguishing between them in the analysis. The reflection of energy off the Earth's surface is typical of Model A drawings, as is the distinct barrier blocking the exit of reflected energy from the Earth's atmosphere. A lack of energy transformation was present in all but one Model A drawing in the sample.

Model B-type drawings also contain an emitting Sun, although energy is not specified as the product being emitted. Drawings of this type typically contain representations of greenhouses, plants, and gases being emitted by these plants (Figure 2 (B)). Drawings aligning strongly with this model may or may not contain a Sun, and generally the drawings contain two completely unrelated components: the Sun and the greenhouse or plants. Model B-type drawings containing a Sun typically do not provide any sense of the role of the Sun in the greenhouse effect process.

Like Model A, Model C drawings contain a Sun emitting energy (Figure 2(C)). This energy, however, never reaches the Earth's surface. Rather, the energy passes through a hole in the atmosphere or the ozone layer, and is absorbed or trapped before fully penetrating the atmosphere. Drawings classified highly in Model C have little deviation from this model, as shown in the student drawing (Figure 2(C)).

Model D drawings represent a subset of drawings containing separate components, similar to the disconnections observed in Model B (Figure 2(D)). Drawings classified in this model do not contain a Sun representation. Rather, disconnected energy enters the Earth's atmosphere. Drawings with high scores in this model also contain depictions of ozone or holes in the atmosphere, as well as a pollution source. These drawings often contain other components, such as reflecting energy as shown in the representative student drawing (Figure 2(D)).

4.3. *Explanation of Variance in Model Scores*

Correlation analysis indicates that higher scores on Model A are related to higher climate change and general science conceptual understanding, more positive attitudes toward learning science, and greater understanding of the nature of science (Table 3). Division of students into two groups, high Model A scorers and low Model A scorers based on median score, indicates that scores on all understanding and attitudes scales are statistically different. Attitudes toward learning science for low Model A (2.88 ± 0.58) and high Model A (3.16 ± 0.69) students are different at $p < .001$ ($t(205) = 3.5$), while nature of science understanding for low Model A (3.53 ± 0.40) and high Model A (3.71 ± 0.38) students are different at $p < .002$ ($t(205) = 3.2$). Understanding of general science for low Model A (3.13 ± 1.41) and high Model A (3.62 ± 1.85) students are different at $p < .05$ ($t(133.5) = 2.0$); understanding of climate science for low Model A (2.77 ± 1.32) and high Model A (3.14 ± 1.30) students are also different at $p < .05$ ($t(205) = 3.2$). Recall that higher scores imply better attitudes and better understanding.

Model B is inversely related to attitudes toward learning science such that the more a drawing aligns with Model B, the more likely the participant is to have lower attitudes toward learning science. Attitudes toward learning science for low Model B (3.02 ± 0.62) and high Model B (2.71 ± 0.72) students are different at $p < .01$ ($t(205) = 2.4$); no other measures showed statistical difference between low and high scorers. Model C did not correlate with any variables nor show statistical difference between scorer levels.

An independent samples *t*-test on normalized factor scores was run to consider the impact of gender and ethnicity on model classification. We analyzed the relationship between factor scores for each of the three models, gender (male and female), and ethnicity (Caucasian and non-Caucasian). Significant differences were observed between

Table 3. Pearson correlations of conceptual understanding, understanding of science, and attitudes toward learning science against model scores

	A	B	C
Climate change conceptual understanding	0.166*	–	–
General science conceptual understanding	0.178*	–	–
Attitude toward learning science	0.273**	0.143*	–
Understanding of the nature of science	0.152*	–	–

*$p < .05$

**$p < .001$

men and women for Model A only. The sample for this model fails Levene's test, indicating that variances are unequal; all reported statistics account for unequal variance. Factor scores for Model A were significantly different for men (0.39 ± 1.0) and women (−0.39 ± 0.83; $t(197.9) = 6.1$, $p < 0.001$). These results indicate that men were more likely than women to draw images representative of Model A. Finally, no significant differences were observed between the ethnicity groups on any of the three models.

Taken together, these data suggest that variance in Model A scores is associated with gender and climate change understanding, general science conceptual understanding, attitudes toward learning science, and understanding of the nature of science. Since no significant interaction terms were observed for the four test scores, a linear regression was run to investigate the extent to which variance in Model A scores could be associated with gender and test variables. Initial results indicated that neither general science nor nature of science scores were significant variables in the regression model. The resultant regression model yielded an R^2 of 0.22, indicating that 22% of the variance in Model A is associated with participant differences in gender, climate change conceptions, and attitude toward learning science ($F_{(3,202)} = 19.1$, mean square due to regression (MSR) = 15.1, $p < .001$). In general, men are more likely to receive a higher Model A score, as are students with stronger conceptual understanding of climate change and better attitudes toward learning science.

4.4. *Comparison with Scientists*

Student drawings were compared to a small sample of experts ($n = 7$) as a validity check on identified representative models. Scientists all displayed perfect scores on the climate change conceptual questions, except for one graduate student who earned four out of six points. Scientists' drawings were much more sophisticated than those of student participants, although only one scientist produced the ideal model (Figure 3). The majority of drawings produced by the scientist group aligned with Model A (Figure 2(A)), with many adding an explicit energy transformation at the Earth's surface.

Certain model characteristics that were prevalent among students were not drawn by scientists, and vice versa (Figure 4). Scientists did not depict greenhouses, pollution, plants, gases being emitted by plants, or ozone or holes in the atmosphere. Depiction of energy absorption at the top of the atmosphere was also absent. Scientists were also much more likely than students to include a Sun in their drawings, and to depict energy moving through the atmosphere to the Earth's surface.

Students generally did not include features in their drawings that are essential for a highly explanatory model (Figure 3(a)). About half of the scientists depicted energy changing at the surface of the Earth and depicted absorption of this energy by greenhouse gases. However, only one scientist depicted re-emission of this energy by greenhouse gases (Figure 3(a)), with most scientists depicting a process similar to Model A (Figure 3(b)). These depictions contained one important component not present in student drawings, namely an explicit energy transformation at the Earth's surface (Figure 5).

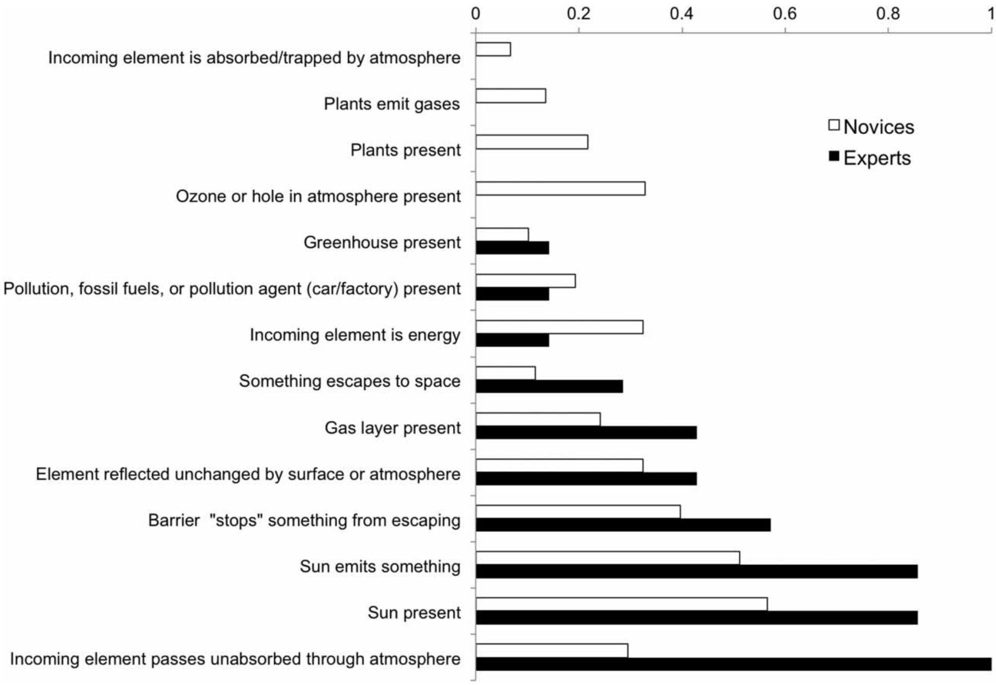

Figure 4. Presence of model components in novice and expert groups

4.5. *Non-cognitive Drawing Components*

Drawings were equally divided between oriented and unoriented drawings, with $n=39$, $n=52$, and $n=91$ drawings containing a left-to-right narrative orientation, a right-to-left orientation, and no specific orientation, respectively. Arrows were used

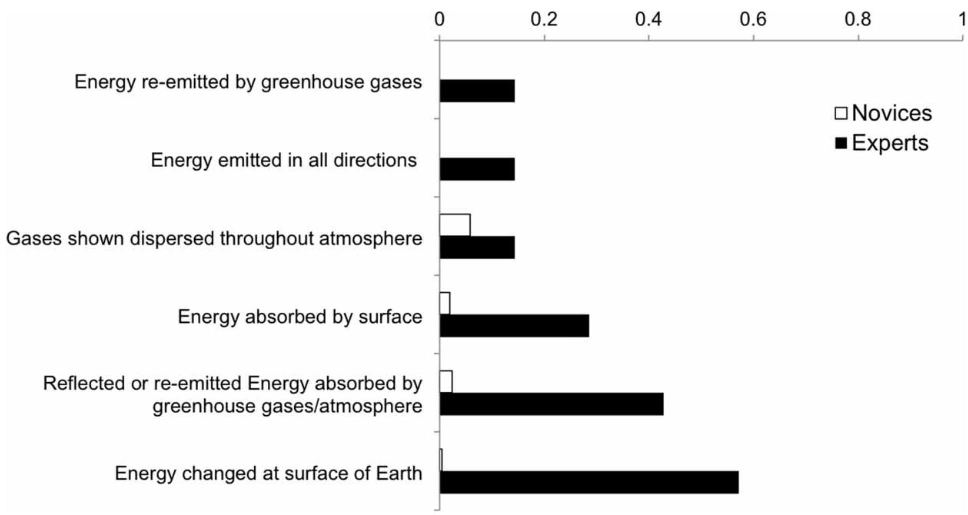

Figure 5. Presence of additional components from the ideal model in novice and expert groups

to depict energy, movement of matter, or to indicate a label, with about three-quarters of drawings containing at least one arrow. Fifty-eight of the drawings contained only abstract features, 140 contained realistic elements, such as cities, and the remaining drawings were too difficult to classify in terms of abstraction/realism.

The relationship of visual narrative directionality and Model A, B, and C scores was considered through comparison of directional (both left-to-right and right-to-left; $n = 91$) and non-directional ($n = 91$) drawings. These directionality groups were significantly different for Model A, as documented by an independent samples *t*-test of factor scores. Model A factor scores for non-directional drawings were significantly different than the scores for the directional group; $t(180) = 6.1$, $p < .001$. These scores were not significantly different for Model B or C at the $p < .05$ level. These results indicate that Model A drawings are more likely to incorporate a directional narrative (either right or left) than non-directional, although we caution that this relationship could be an artifact of the coding process itself.

The relationship between the presence of realistic elements in drawings and model scores was considered through comparison of drawings which contained only abstract features, such as lines, boxes, and arrows, and those which contained features that represented physical phenomena. For example, the Sun could be depicted abstractly as a word or realistically through a drawing of a circle with radial lines. Drawings containing abstract elements were more likely to receive higher scores in Model A; $t(117.6) = 4.0$, $p < .001$. No differences were observed for either Model B or C scores at the $p < .05$ level.

For all three models (A, B, C), models containing arrows representing energy received higher overall scores. Arrows representing matter movement were negatively related to scores in the case of Model A; $t(205) = 3.5$, $p < .001$. The use of arrows as labels did not correlate to Model A with statistical significance at $p < .05$, although significance was achieved at a slightly higher value ($p = .09$). Based on these data overall, we considered the extent to which all three arrow types could be used to predict a student's Model A score, coupled with the earlier regression against gender, conceptions, and attitude. The regression included the three arrow types, and the variables already explaining 22% of the variance in the Model A score, as in Table 3. The resultant regression model yielded $R^2 = 0.516$, indicating that an additional 29.6% of the variance in Model A is associated with participant use of the three arrow types ($F_{(3,203)} = 56.4$, MSR = 31.2, $p < .001$). The use of energy arrows dominates this regression model, while the use of arrows to depict moving matter was negatively related to Model A.

5. Discussion

The factor analytic approach presented here provides insight into not only student alternative conceptions, but also the ways in which individual alternative conceptions are held within larger explanatory models. Rather than documenting the percentage of students who hold a single alternative conception, the factor analytic approach allows a detailed look into where each idea sits within a larger model. For example, two students with the alternative conception that ozone holes play a role in the greenhouse effect are not necessarily reasoning from similar positions. One student may have a Model D approach, wherein disconnected pieces of information will severely limit the ability to draw conclusions or make predictions in the context of changes to energy or greenhouse gas inputs. A second student may incorporate an ozone hole into a Model A perspective. This student would not be hindered by the ozone feature, and in most cases the ozone hole alternative conception would likely have little impact on the ability to reason and make predictions. Thus, understanding the broader model underlying individual alternative conceptions is more important than recognizing the existence of the conception itself.

This work clearly identifies the presence of four dominant models that our study population (incoming freshmen at a large Midwestern institution) holds about the greenhouse effect. These models align in some ways with prior work on younger students, while also pointing out the limitations of visual inspection for identifying patterns in drawings.

All of the alternative conceptions identified in our work are present in the research as reported in Shepardson et al. (2009, 2011). In addition, two of the models of Shepardson et al. (2011) align with Model A and Model B identified in this study, indicating that the factor analytic approach is reliably reproducing prior work. While the concept of ozone or holes in the atmosphere is present in both Models C and D of this study, Shepardson et al. (2011) amalgamate these models into one model, possibly obscuring differences in reasoning ability for students who, while holding the ozone misconception in common, hold different overarching mental models of the greenhouse effect. We also note that Model D of this study is essentially one that groups together students who hold disconnected pieces of information. The recognition that a drawing may represent individual ideas, rather than an aggregated mental model, is quite important, especially since the discussion of whether people reason from integrated models (e.g. Chi, De Leeuw, Chiu, & Lavancher, 1994) or from fragmented pieces of information (e.g. diSessa, 1993) suggests that both integrated and disconnected models are present within the student population.

Important differences arose between previous work and this study. We suggest that these differences arise for two reasons. First, existing work focuses on younger students, who are likely to hold some models not present in the college population, and vice versa. Second, existing work relies on human generation of groups, not on a computer model analyzing connections and relationships between drawing components. Given the limitations of human scoring abilities, particularly the limits in efficiency and the labor-intensive nature of generating and applying a holistic coding rubric, we encourage the deconstruction of drawings into salient features and the use of computer approaches, such as the factor analysis used here. Statistical analysis of drawings can then become an effective tool for illuminating patterns in large drawing data sets.

The finding that students with better understanding of climate change and better attitudes toward learning science are more likely to hold the most sophisticated model (A) aligns with expectations. Observed gender differences in Model A scores, suggesting that men are more likely than women to score highly on Model A, align with the general findings that men tend to score higher on science assessments (e.g. Young & Fraser, 1993) and warrants investigation in its own right. Similarly not surprising, students who hold the model most misaligned with a scientific perspective (B) are also likely to have lower attitudes toward learning science. More interesting are the relationships between non-cognitive elements in drawings and model scores; we limit our discussion to Model A as it showed the only statistically significant relationships with non-cognitive variables. First, the finding that drawings with higher Model A scores were more likely to contain a directional narrative might suggest that students reasoning from Model A actually hold an integrated mental model; that is, fragmented ideas would be much more likely to be represented in a non-directional, non-narrative drawing. Abstract drawings were also more likely to score highly in Model A. This may result from students' recognizing the model as a model, rather than an actual representation of the natural world. Finally, and perhaps most interesting, is the relationship between types of arrows used and Model A scores. Students who used arrows to indicate different types of energy were more likely to receive high Model A scores, while students who used arrows to depict movement of matter were likely to receive low Model A scores. This relationship makes sense given that the greenhouse effect is fundamentally about energy moving and transforming; matter in the greenhouse effect interacts with energy, but does not move itself. Students depicting movement of matter tended to be depicting gases emitting from plants, in alignment with Model B, or gases being emitted by pollution sources, as in Model D. The relationship of non-cognitive drawing variables to underlying models also warrants future research, especially where drawings can be used to reduce anxiety while simultaneously increasing conceptual understanding.

5.1. *Implications for Research*

Manual inspection is the most common approach used by researchers interested in understanding the internal mental models that are made explicit through drawing. This manual inspection most commonly takes the form of indexing and results in documentation of the prevalence of features present in analyzed drawings. Occasionally, researchers will group features together in an attempt to articulate the integrated nature of underlying mental models. Either approach necessarily takes significant time as individual researchers must analyze drawings by hand, and often interrater reliability is established through repeat analysis of the same drawings. This manual approach is quite effective at revealing the set of scientific and alternative conceptions that participants hold about the drawn phenomena; it is much less effective at revealing the way in which these conceptions are connected together. That is, manual inspection is an inaccurate method for revealing underlying patterns in drawing data.

Computer grouping of drawings, on the other hand, is quite effective at revealing underlying patterns. The rapid analysis made possible by computer algorithms means that drawing analysis may take only seconds, rather than the long timescales needed for manual inspection. Computer grouping approaches are only limited by the extent to which the researcher is able to pre-define symbologies of interest; this is in fact the major drawback of existing drawing analysis systems. Each type of drawing would require input of a set of relevant symbologies, effectively meaning that analysis can only occur on a limited set of drawing types. Computers are also unable to interpret the meaning behind symbologies, unlike the human researcher who can draw conclusions based on background knowledge of the subject area.

The factor grouping approach proposed here takes advantage of the best features of manual and computer approaches, albeit with limitations. The factor grouping approach starts with manual inspection in that researchers must deconstruct exemplar drawings into salient features. This analysis requires sufficient knowledge of the subject area to allow for identification of relevant, scientific features as well as common alternative conceptions that may be important components of non-scientific explanatory models. The presence or absence of salient features also generally must be completed by hand given the significant variation in individual depictions of a common feature. Once salient features are identified for a set of drawings, however, underlying mental models can be revealed through any computer-based pattern analysis, such as the factor analysis used here. This approach certainly takes much more time than simple indexing or a standard computer grouping study, although is faster than attempts to manually group drawings into categories. Development of computer-based mechanisms for conducting pattern analysis based on salient features, or for training computers to recognize salient features, would be a significant step forward in drawing analysis techniques.

We would also encourage researchers to include religiosity and political affiliation, particularly those in fields like discipline-based education research where such collection is not routine and for concepts like climate change or evolution that can be politically or religiously charged. Studies of general science understanding suggest that ideology, whether religious or political, correlates strongly with scientific literacy, including nature of science understanding, and attitudes toward science (e.g. Evans & Durant, 1995; Sherkat, 2011). Relative to climate change, the propensity to agree that climate change is a factual and/or important phenomenon corresponds to both political affiliation (Fielding, Head, Laffan, Western, & Hoegh-Guldberg, 2012; McCright & Dunlap, 2011) and religiosity (Wardekker, Petersen, & van der Sluijs, 2009). Although religion and political affiliation were not measured in this study, attitudes toward science and conceptual understanding of climate change were measured and are known to correlate with these ideological variables (e.g. McCright & Dunlap, 2011; Sherkat, 2011).

5.2. *Implications for Instruction*

While the factor analytic approach described here is interesting from a purely research perspective, we find that this work has powerful implications for instruction. As a formative tool, identifying archetype models held by students provides recognizable ‘straw men’ that instructors can work against in explaining scientific models.

Early in instruction, students can generate their own drawings and compare these to the archetypes to see which archetypes their drawings most closely resemble. Scenarios can then be provided that create a cognitive dissonance between archetypes and phenomena. For example, students who align with Model A might predict an increase in global warming during times when the Earth's surface is covered with more snow and ice, and hence is more reflective. This is exactly opposite of reality, where we know that increased reflectance (or albedo) will result in more energy escaping into space and hence a colder planet. On Earth, incoming light that is reflected off the earth generally passes into space unabsorbed. Students are hence faced with a dissonance—the disconnect between model predictions and real-world observations. This type of cognitive challenge has been shown to be highly effective in eliciting conceptual change of mental models (e.g. Posner, Strike, Hewson, & Gertzog, 1982).

The fact that experts reason from more sophisticated, yet not necessarily perfectly correct, models has important implications for what we expect students to understand post-instruction. The experts in this study generated models that were highly explanatory and predictive, and explained basic processes that are necessary for climate literacy as a thinking citizen. Thus, these expert-generated individual models may provide insight into the model complexity that we should be teaching in our classrooms. In addition, the misalignment between scientist drawings and the consensus model offers an opportunity to think about, and perhaps discuss with students, the nature of scientific models as consensus, rather than perfectly accurate, models of the natural world.

No method, whether based on interviews, short answers, drawings, or observation and explanation, is perfect in assessing the internal mental model of students. Despite this, we argue that the use of student drawings adds another valuable assessment approach that can complement written or oral data sets. In particular, drawings offer the significant benefit of decreasing affective barriers to engagement (Alsop & Watts, 2003). Research in other areas indicates that anxiety is reduced when participants are encouraged to draw, rather than simply verbalize, their experience (e.g. Chapman, Morabito, Ladakakos, Schreier, & Knudson, 2001), while testing holds its own negative barriers to achievement (e.g. Paulman & Kennelly, 1984). We suggest that the anxiety inherent to test taking could be reduced when students are encouraged to draw explanations rather than simply write their responses. Increased relaxation and engagement with the material may lead to more accurate representation of student understanding, and better test performance overall.

6. Conclusions

Drawings provide a unique window into human cognition, both because of the inherent opportunity to build seamless connections between concepts without potential verbal barriers and the blending of cognitive and affective aspects of human thought. Although drawings have been used in studies of student conceptions for over a century, the approaches used to analyze drawings are surprisingly limited. In most cases, researchers rely on limited individual working memory to organize drawings into conceptual groups, and then report on the prevalence of these groupings within a population.

Working from a laundry list of alternative conceptions to inform instruction is simply unfeasible. Every student is different, and every student would require their own personal intervention to address their unique set of alternative conceptions. Given this, it is extremely important to identify the sets of student ideas that together make the models through which the majority of students are likely filtering science instruction. In addressing a limited set of models that incorporate many individual alternative conceptions, instruction is more realistically able to scaffold a broad set of students from their own ideas toward scientific models.

This work builds from the examples set in other fields by taking advantage of computers to move from human perception-based to computation-based analysis. In many ways, we approached drawings as a linguist might consider the words and grammar of a sentence. In considering specific elements in a drawing, we were able to both observe the presence of individual conceptual elements and look for connections between those elements. This approach provides a reproducible mechanism for evaluating student models, generating a valid measure of student understanding that can be used in designing instruction or in assessing student learning.

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References

Ainsworth, S., Prain, V., & Tytler, R. (2011). Drawing to learn in science. *Science*, *333*(6046), 1096–1097. doi:10.1126/science.1204153

Alerby, E. (2000). A way of visualising children's and young people's thoughts about the environment: A study of drawings. *Environmental Education Research*, *6*(3), 205–222. doi:10.1080/13504620050076713

Alsop, S., & Watts, M. (2003). Science education and affect. *International Journal of Science Education*, *25*(9), 1043–1047. doi:10.1080/0950069032000052180

Bacharach, V. R., Baumeister, A. A., & Furr, R. M. (2003). Racial and gender science achievement gaps in secondary education. *The Journal of Genetic Psychology*, *164*(1), 115–126.

Bowker, R. (2007). Children's perceptions and learning about tropical rainforests: An analysis of their drawings. *Environmental Education Research*, *13*(1), 75–96. doi:10.1080/13504620601122731

Brown, J. M., Henderson, J., & Armstrong, M. P. (1987). Children's perceptions of nuclear power stations as revealed through their drawings. *Journal of Environmental Psychology*, *7*(3), 189–199. doi:10.1016/S0272-4944(87)80029-4

Carney, R. N., & Levin, J. R. (2002). Pictorial illustrations still improve students' learning from text. *Educational Psychology Review*, *14*(1), 5–26.

Chapman, L., Morabito, D., Ladakakos, C., Schreier, H., & Knudson, M. M. (2001). The effectiveness of art therapy interventions in reducing post traumatic stress disorder (PTSD) symptoms in pediatric trauma patients. *Art Therapy*, *18*(2), 100–104. doi:10.1080/07421656.2001.10129750

Cheng, M., & Gilbert, J. K. (2009). Towards a better utilization of diagrams in research into the use of representative levels in chemical education. In P. J. K. Gilbert, & P. D. Treagust (Eds.), *Multiple representations in chemical education* (pp. 55–73). Springer. Retrieved from http://link.springer.com/chapter/10.1007/978-1-4020-8872-8_4

Chi, M. T. H., De Leeuw, N., Chiu, M. H., & Lavancher, C. (1994). Eliciting self-explanations improves understanding. *Cognitive Science*, *18*(3), 439–477. doi:10.1016/0364-0213(94)90016-7

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction*, *10*(2–3), 105–225. doi:10.1080/07370008.1985.9649008

Evans, G., & Durant, J. (1995). The relationship between knowledge and attitudes in the public understanding of science in Britain. *Public Understanding of Science*, *4*(1), 57–74.

Fielding, K. S., Head, B. W., Laffan, W., Western, M., & Hoegh-Guldberg, O. (2012). Australian politicians' beliefs about climate change: Political partisanship and political ideology. *Environmental Politics*, *21*(5), 712–733.

Fischer, A., & Young, J. C. (2007). Understanding mental constructs of biodiversity: Implications for biodiversity management and conservation. *Biological Conservation*, *136*(2), 271–282. doi:10.1016/j.biocon.2006.11.024

Forbus, K., Usher, J., Lovett, A., Lockwood, K., & Wetzel, J. (2011). CogSketch: Sketch understanding for cognitive science research and for education. *Topics in Cognitive Science*, *3*(4), 648–666. doi:10.1111/j.1756-8765.2011.01149.x

Harrison, A. G., & Treagust, D. F. (1996). Secondary students' mental models of atoms and molecules: Implications for teaching chemistry. *Science Education*, *80*(5), 509–534. doi:10.1002/(SICI)1098-237X(199609)80:5<509::AID-SCE2>3.0.CO;2-F

Karpudewan, M., Roth, W. M., & Abdullah, M. N. S. B. (2014). Enhancing primary school students' knowledge about global warming and environmental attitude using climate change activities. *International Journal of Science Education*, 1–24. doi:10.1080/09500693.2014.958600

Lambert, J. L., Lindgren, J., & Bleicher, R. (2011). Assessing elementary science methods students' understanding about global climate change. *International Journal of Science Education*, *34*(8), 1167–1187. doi:10.1080/09500693.2011.633938

Leiserowitz, A. (2006). Climate change risk perception and policy preferences: The role of affect, imagery, and values. *Climatic Change*, *77*(1–2), 45–72. doi:10.1007/s10584-006-9059-9

Liarakou, G., Athanasiadis, I., & Gavrilakis, C. (2011). What Greek secondary school students believe about climate change? *International Journal of Environmental and Science Education*, *6*(1), 79–98.

Libarkin, J. C. (2001). Development of an assessment of student conception of the nature of science. *Journal of Geoscience Education*, *49*(5), 435–442.

Libarkin, J. C., Ward, E. M. G., Anderson, S. W., Kortemeyer, G., & Raeburn, S. P. (2011). Revisiting the Geoscience Concept Inventory: A call to the community. *GSA Today*, *21*, 26–28. doi:10.1130/G110GW.1

Lombardi, D., & Sinatra, G. M. (2012). College students' perceptions about the plausibility of human-induced climate change. *Research in Science Education*, *42*(2), 201–217.

Lowe, T., Brown, K., Dessai, S., de França Doria, M., Haynes, K., & Vincent, K. (2006). Does tomorrow ever come? Disaster narrative and public perceptions of climate change. *Public Understanding of Science*, *15*(4), 435–457. doi:10.1177/0963662506063796

Maibach, E., Witte, J., & Wilson, K. (2011). 'Climategate' undermined belief in global warming among many American TV meteorologists. *Bulletin of the American Meteorological Society*, *92*, 31–37. doi:10.1175/2010BAMS3094.1

Mayer, R. E. (1989). Systematic thinking fostered by illustrations in scientific text. *Journal of Educational Psychology*, *81*(2), 240–246.

McCaffrey, M., & Buhr, S. (2008). Clarifying climate confusion: Addressing systemic holes, cognitive gaps, and misconceptions through climate literacy. *Physical Geography*, *29*(6), 512–528. doi:10.2747/0272-3646.29.6.512

McCright, A. M., & Dunlap, R. E. (2011). The politicization of climate change and polarization in the American public's views of global warming, 2001–2010. *The Sociological Quarterly*, *52*(2), 155–194.

Moser, S. C. (2010). Communicating climate change: History, challenges, process and future directions. *Wiley Interdisciplinary Reviews: Climate Change*, *1*(1), 31–53. doi:10.1002/wcc.11

Myers, O. E., Saunders, C. D., & Garrett, E. (2003). What do children think animals need? Aesthetic and psycho-social conceptions. *Environmental Education Research*, *9*(3), 305–325. doi:10.1080/13504620303461

Papadimitriou, V. (2004). Prospective primary teachers' understanding of climate change, greenhouse effect, and ozone layer depletion. *Journal of Science Education and Technology*, *13*, 299–307. doi:10.1023/B:JOST.0000031268.72848.6d

Patton, M. Q. (2002). *Qualitative research and evaluation methods* (3rd ed.). Thousand Oaks, CA: Sage Publications.

Paulman, R. G., & Kennelly, K. J. (1984). Test anxiety and ineffective test taking: Different names, same construct? *Journal of Educational Psychology*, *76*(2), 279–288. doi:10.1037/0022-0663.76.2.279

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, *66*(2), 211–227.

Pruneau, D., Liboiron, L., Vrain, E., Biosphère, L., Gravel, H., Bourque, W., & Langis, J. (2001). People's ideas about climate change: A source of inspiration for the creation of educational programs. *Canadian Journal of Environmental Education (CJEE)*, *6*(1), 121–138.

Punter, P., Ochando-Pardo, M., & Garcia, J. (2010). Spanish secondary school students' notions on the causes and consequences of climate change. *International Journal of Science Education*, *33*(3), 447–464. doi:10.1080/09500693.2010.492253

Ross, R. M., Duggan-Haas, D., & Allmon, W. D. (2013). The posture of *Tyrannosaurus rex* : Why do student views lag behind the science? *Journal of Geoscience Education*, *61*(1), 145–160. doi:10.5408/11-259.1

Shepardson, D. P., Choi, S., Niyogi, D., & Charusombat, U. (2011). Seventh grade students' mental models of the greenhouse effect. *Environmental Education Research*, *17*(1), 1–17. doi:10.1080/13504620903564549

Shepardson, D. P., Niyogi, D., Choi, S., & Charusombat, U. (2009). Seventh grade students' conceptions of global warming and climate change. *Environmental Education Research*, *15*(5), 549–570. doi:10.1080/13504620903114592

Sherkat, D. E. (2011). Religion and scientific literacy in the United States. *Social Science Quarterly*, *92*(5), 1134–1150.

Smith, G. A., & Bermea, S. B. (2012). Using students' sketches to recognize alternative conceptions about plate tectonics persisting from prior instruction. *Journal of Geoscience Education*, *60*(4), 350–359. doi:10.5408/11-251.1

Smith, K. J., & Metz, P. A. (1996). Evaluating student understanding of solution chemistry through microscopic representations. *Journal of Chemical Education*, *73*(3), 233. doi:10.1021/ed073p233

Sterman, J. D. (2011). Communicating climate change risks in a skeptical world. *Climatic Change*, *108*, 1–16.

Svihla, V., & Linn, M. C. (2012). A design-based approach to fostering understanding of global climate change. *International Journal of Science Education*, *34*(5), 651–676.

Sweeney, L. B., & Sterman, J. D. (2007). Thinking about systems: Student and teacher conceptions of natural and social systems. *System Dynamics Review*, *23*(2-3), 285–311. doi:10.1002/sdr.366

Tabachnick, B. G., & Fidell, L. S. (2001). *Using multivariate statistics*. Boston: Allyn and Bacon.

Trumbo, J. (1999). Visual literacy and science communication. *Science Communication*, *20*(4), 409–425. doi:10.1177/1075547099020004004

Ungar, S. (2000). Knowledge, ignorance and the popular culture: Climate change versus the ozone hole. *Public Understanding of Science*, *9*(3), 297–312. doi:10.1088/0963-6625/9/3/306

Van Meter, P., & Garner, J. (2005). The promise and practice of learner-generated drawing: Literature review and synthesis. *Educational Psychology Review*, *17*(4), 285–325. doi:10.1007/s10648-005-8136-3

Wardekker, J. A., Petersen, A. C., & Van Der Sluijs, J. P. (2009). Ethics and public perception of climate change: Exploring the Christian voices in the US public debate. *Global Environmental Change*, *19*(4), 512–521.

Weber, E. U., & Stern, P. C. (2011). Public understanding of climate change in the United States. *American Psychologist*, *66*(4), 315–328.

Whitmarsh, L. (2009). What's in a name? Commonalities and differences in public understanding of 'climate change' and 'global warming'. *Public Understanding of Science*, *18*(4), 401–420.

Young, D. J., & Fraser, B. J. (1993). Socioeconomic and gender effects on science achievement: An Australian perspective. *School Effectiveness and School Improvement*, *4*(4), 265–289. doi:10.1080/0924345930040403