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Running Head: ORBIT DIAGRAMS AND THE SEASONS

How different variants of orbit diagrams influence student explanations of the seasons

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Abstract

The cause of the seasons is often associated with a very particular alternative conception: that the Earth's orbit around the sun is highly elongated and the differences in distance result in variations in temperature. It has been suggested that the standard diagrams used to depict the Earth's orbit may be in some way responsible for the initial appearance and overall maintenance of this incorrect conceptualization; the elongated shape of the orbit is thought of as a *conceptualization cue* that invites a fairly predictable way of reasoning. To test if that is indeed the case, six variants of diagrams depicting differently shaped Earth orbits around the sun were presented to 652 ninth-grade students in the United States. From responses to a written assessment, students' ideas about what caused the seasons were identified and analyzed. Elongation of orbit did not appear to have an effect, and there was no reinforcement effect for students who initially believed in an elongated orbit. Additional analyses show instead that other features in the diagrams can instead be more influential as conceptualization cues, such as shading or overlapping shapes, but those cues' influence on student reasoning depend on which other cues accompany them.

1 Introduction

Diagrams play a central role in the knowing, communicating, teaching, and learning of science (Hegarty, Carpenter, & Just, 1990; Macdonald-Ross, 1979; Roth, Pozzer-Ardenghi, & Han, 2005). There are a number of reasons as to why diagrams have been considered special for science, ranging from the sociological (Latour, 1987) to the more aesthetic (e.g., Tufte, 1983). What is of present interest is the conceptual influence that is exerted by diagrams. Diagrams are valued, at least in part, because they are thought to alter or enhance cognitive capabilities. For example, in a classic paper, Larkin & Simon (1987) illustrated how diagrams of pulley systems fundamentally change the reasoning patterns one must follow in order to draw inferences compared to other symbolic representational formats. These are issues that continue to receive significant attention in cognitive science (e.g., Heiser & Tversky, 2006; Stenning & Oberlander, 1995) and across other psychologically oriented disciplines (Glasgow, Narayanan, & Chandrasekaran, 1995).

Like other kinds of inscriptions, or representations, diagrams highlight certain features of a depicted situation at the expense of obscuring others. With certain features highlighted, it is natural to expect that certain modes of thinking or certain ideas associated with highlighted features would be privileged. Designed carefully, certain sequences of diagrams could be used in a strategic manner by helping to move students along a specific learning trajectory. Of course, for this to be possible, the assumption must be made that a representation exerts enough influence to keep students moving along that trajectory. Therefore, a general question must be asked of all diagrams that are used in science instruction: Do the highlighted features promote the generation of intended interpretations and understandings of the scientific ideas that are being represented? Or might those well-intentioned diagrams lead students astray?

The goal of this paper is to consider those questions as they relate to a notoriously difficult idea in astronomy and earth science education: the cause of seasonal temperature variation. Across the research literature on misconceptions associated with the seasons, the most frequently noted misunderstanding of why we have different average temperatures across seasons involves imagining that the Earth following a highly eccentric elliptical orbit that causes us to be farther from the sun in the winter and closer to the sun in summer (Atwood & Atwood, 1996; Trumper, 2006). Conventional wisdom and several researchers (e.g., Duschl, Schweingruber, & Shouse, 2007; e.g., Kikas, 1998; Mishra, 1999) have suggested that commonly used variants of orbit diagrams, in which the orbit is drawn as an exaggerated elliptical shape in an effort to render *perspective*, will induce the common misconception that the colder seasons on Earth are the product of greater distance of the Earth from the sun. It is a sensible claim to make in that the exaggerated elliptical shape that is shown in such diagrams does bear resemblance to drawings that students make when providing a 'closer-farther' explanation (Figure 1).

[INSERT Figure 1 AROUND HERE]

To illustrate how attractive of an idea this has become, I refer to an example from a recent high-profile consensus report prepared for the National Research Council regarding science education in the United States (Duschl, et al., 2007). The authors of this report had done a number of important syntheses, and they can be credited for some of the most recent interest and attention to learning progressions in the science education community.

Beyond that work, the authors also reported on the leading thinking in other aspects of science teaching and learning. With respect to diagrams, they noted:

> "Diagrams [in science instruction] can be difficult to understand for a host of reasons. Sometimes the desired information is missing in the first place; sometimes, features of the diagram unwittingly play into an incorrect preconception. For example, it has been suggested that the common student misconception that the earth is closer to the sun in the summer than in the winter may be due in part to the fact that two-dimensional representations of the three-dimensional orbit make it appear as if the foreshortened orbit is indeed closer to the sun at some points than at others."(Duschl, et al., 2007 p. 158)

The selected excerpt of the report falls in line with observations and concerns voiced by numerous others regarding the anticipated difficulties associated with the commonly used two-dimensional diagrams of three-dimensional orbits (e.g., Barab, Hay, Barnett, & Keating, 2000; Kikas, 1998; Mishra, 1999; Schnepps & Sadler, 1988; Yu & Sahami, 2008).

In this paper, I will show that the relationship between those perspective-rendered orbit diagrams and students' ideas about the cause of the seasons are far more nuanced than the literature would suggest. Specifically, there does not appear to be evidence that the elliptical shape induces nor strengthens the closer-farther misconception. I will also explore some other potentially troubling features that commonly appear in commercialized versions of orbit diagrams and discuss how those features can exert their own influence, but only in the company or absence of other specific visual features. These findings raise new questions regarding the relationship between depiction and conceptualization and help to map out some of the complexities with respect to how a diagram influences reasoning in a scientific domain.

In the sections that follow, I will first discuss some of the motivation for pursuing this work. While there has been much recent interest in the use of diagrams amidst the science education community, I had found similar results in some earlier, smaller-scale research that motivated the present quasi-replication. Following discussion ofthat previous work, I will make explicit what I consider to be the core assumption behind the diagram-conceptualization claims. They involve what I refer to as 'conceptualization cues', for which their assumed existence and influence is rationalized by literatures that exist in cognitive and perceptual psychology. I then describe the experiment I performed to determine if specific conceptualization cues indeed exert the predicted influences. Discussion of some unexpected findings and some implications for science research and instruction follow. Finally, I discuss a few limitations in the current study.

2 Motivation for the present work

In an earlier study, I examined the influence of common variants of textbook diagrams on student reasoning across a number of science content areas within a one-on-one interview context (Lee, 2008, 2010). Having noted that there were numerous occasions in which specific interpretations or ways of thinking around specific diagrams were determined as being likely in the literature (e.g., American Association for the Advancement of Science, 2002; Carvalho, Silva, & Clement, 2007; Cho, Kahle, & Nordland, 1985; Colin, Chauvet, & Viennot, 2002; Schnepps & Sadler, 1988; Stern & Roseman, 2004;

Wampler, 2002), I had sought to find empirical support to bolster extant claims about the utility of specific versions of diagrammatic representations. The results of that study showed a surprising lack of correspondence between modified features of the examined representations and the ideas students offered about the represented system or phenomena. This held true especially for orbit diagrams and how students reasoned about the seasons (Lee, 2010). There, and in the other examined physical science content areas, students did not appear to follow the incorrect conceptual pathways that the diagrams where purportedly most likely to lead them.

That earlier study was limited in that it was a sample of 24 students, and it took place in a semi-structured interview format. While there are many benefits to using interview data, some influence from the interviewer could plausibly have resulted in an interaction by which a conceptualization attributed to the interviewed student was actually jointly constructed by the interviewer and interviewee (Roth, 2008; Roth & Middleton, 2006). Regardless, the absence of a clear relationship between classes of representations and students' conceptualizations from that sample was surprising and ultimately motivated the present study. The current study increased the number of students substantially and involves a different methodological approach (a written assessment administered by teachers) that provided greater distance between the researcher and the research participants. This methodological change was made in order to further decrease likelihood of immediate researcher bias and increase the potential for generalizability.

In addition to the personal interest in further testing early and initial findings, there was an interest in speaking to current concerns within the science education community. Recently, there have been scholars such as Cook and colleagues who have been exploring how students interpret and make sense of diagrams in science, noting that this has been a longstanding area of interest for educators and educational psychologists (Cook, 2006; Cook, Wiebe, & Carter, 2008). Cook's approach has focused largely on how prior content knowledge influences the ways in which students look at and make sense of canonical diagrams. Other work by Roth and colleagues has also explored the comprehension of diagrams and other graphic inscriptions in text materials (Han & Roth, 2006; Roth, et al., 2005). In that work, it is noted that despite their prevalence in curricular materials, firm understandings of how students use or process such figures has been surprisingly lacking among science educators. They offer semiotic and anthropological frameworks to help make progress in building our understanding of how inscriptions are understood. Mayer has also produced a substantial amount of research on diagrams as part of his program of multimedia learning research (Mayer, 1997, 2001). His approach has been to examine domain general principles that influence diagram interpretation. My current approach differs in that my intention is to firmly situate the present study in the specifics of a particular science topic (i.e., the seasons). My goal is to critically examine the claims that are made about how a commonly used, and somewhat contentious, diagram affects students' scientific ideas. Obviously, there are advantages and disadvantages to this approach. The present work does not make claims that will easily generalize beyond the domain of study. However, it does serve as a detailed case that can illustrate some of the complexity that may be latent in other domains that are often associated with specialized diagrams.

Moreover, there has been a recent interest in the science education community around the scientific practice of *modeling*. Modeling involves iterative generation, testing, and refinement of conceptualized relationships and entities, and it intimately involves the use of inscriptions, such as diagrams (e.g., Achér, Arca, & Sanmarti, 2007; Schwarz, et al., 2009). The relationship of diagrams to the modeling practice has been so close that the terms 'model' is often mistakenly used in place of what would be presently referred to as a diagram (Treagust, Chittleborough, & Mamiala, 2002). The distinction to be drawn is that diagrams are one particular kind of inscription. A model can be augmented by and communicated through that inscription, but it is not reducible to the inscription alone (Treagust, et al., 2002).

Finally, the seasons have been a notoriously challenging and fruitful area for the study of prior conceptions, learning, and conceptual change. Some of the most widely cited research on prior and alternative conceptions has come from studies of the seasons (Atwood & Atwood, 1996; Newman & Morrison, 1993; Sadler, 1987; Trumper, 2006). The explanation of the elongated Earth's orbit causing seasonal temperature variation is a common alternative conception, noted to be the most frequent among many previous research studies. Clearly, that explanation has an intuitive appeal, as increased distance from a heat source (i.e., the sun) is well understood as resulting in less heat for a given body (i.e., the Earth in winter). The problem with this explanation is that it does not account for the fact that the Northern and Southern hemispheres experience opposite seasonal patterns. Furthermore, it does not consider the more consistent range of temperatures experienced by equatorial regions of the Earth.

The fact is that as the Earth orbits the sun, it does follow an elliptical path. At a certain time of the year, the Earth is closer to the sun than any other time. Many students are aware of this fact, and that provides some further justification for their sense that the seasons are the product of orbital distance. What many students fail to consider is that the point of minimal distance (the perihelion) occurs when the Northern hemisphere is experiencing winter. Sometimes this detail is presented in K-12 textbooks, but is more often reserved for college level science instruction.

Also, given the sheer difference in scale between the Earth and sun and the tremendous distance between the two, differences in orbital distance are more or less inconsequential. The fact that the Earth rotates along a tilted axis is what causes the seasonal temperature variation, as it affects the angle of incidence of solar energy that travels to the sun. Teaching this is a challenging endeavor (Salierno, Edelson, & Sherin, 2005; Willard & Roseman, 2007). Although it requires a great deal of thoughtful planning, instruction can be effectively designed to help students learn this content, as illustrated recently by Hsu (2008).

3 Conceptualization cues

In this section I intend to identify the notion of 'conceptualization cues' that have been generally associated diagrams in the literature. The goal here is to explicitly distinguish a family of claims and suggestions that have been made by many other science educators regarding how diagrams influence conceptual understanding, and in doing so, I intend to find some theoretical grounding that explains why those claims are sensible ones to make. The grounding I consider comes out of cognitive and perceptual psychology. This paper can be seen as serving to test the anticipated influence of a set of conceptualization cues in a particular science content domain.

The central idea regarding conceptualization cues is that there are particular features or elements in a diagram, or cues, that are expected to privilege a certain coalescence of conceptual ideas. The case I will examine involves the elliptical depictions of orbits and the anticipated closer-farther explanation of the seasons. Other examples in the literature include the use of borders or background colors in drawings of molecules cuing ideas of containment (American Association for the Advancement of Science, 2002; Kesidou & Roseman, 2002), the use of arrow colors in food web diagrams cuing misdirection of energy (Stern & Roseman, 2004), the use of shape occlusion in anatomy drawings cuing disorder (Carvalho, et al., 2007), the use of straight lines in cladograms cuing an absence of evolutionary change (Meir, Perry, Herron, & Kingsolver, 2007), and the use of partitions and boundaries in Punnet squares cuing ideas about pre-determined genetic outcomes (Cho, et al., 1985).

Cognitive and perceptual psychology are areas of research in which there has been substantial discussion of visual cues, particularly as they relate to object recognition and image interpretation (Medin, Ross, & Markman, 2001). In visual information processing, we are always taking what is more or less a two dimensional array of information (represented by the activations of cells that make up a the surface of the retina) and are translating those into ideas about space and object relations in the physical or depicted world. To effectively do that work, we rely on specific visual cues. For example, to determine depth, cues that are considered include interpositionality, relative size, and shape deformations are often considered. Given two instances of identical objects placed in front of a viewer, the larger one will often be construed as being closer. If the contours of an assumed shape are disrupted, our adherence to general shape and continuity principles will lead us to infer that one object is in front and the other is behind. Use of shadow and shading can also be an important cue that influences how we perceive shape or positional relationships (Cavanagh & Leclerc, 1989) because of our perception of where a light source is and how an object blocks travelling light. In general, the more cues that are present, the more likely we are to infer a particular feature (Cutting & Vishton, 1995; Kunnapas, 1968). This would suggest that problematic representations of the Earth's orbit might be deficient in that they simply do not provide sufficient cues for what is being depicted. That could explain why elliptical depictions of the orbit are problematic, as it is not clear from those types of diagrams that depth should be perceived (Schnepps & Sadler, 1988).

The influence of cues is often described in a bottom-up fashion; information is read from the world and then constructed and reassembled into a whole upon further processing. When an image is designed poorly, the cues may confuse a viewer and lead them to incorrect interpretations. However, it has been well-established that a pre-established schema can influence perception in a top-down manner (Carr, McCauley, Sperber, & Parmelee, 1982; Hochberg & Hochberg, 2007). Given some prior knowledge about what is being depicted, certain cues will be weighted more heavily as an interpretation is constructed. The implication for science learning is that students who already have an incorrect preconception of some scientific idea will attend specifically to features or cues that support the incorrect idea. This idea parallels, in some ways, the work of Kuhn around children's commitment to theories and how they attend to or consider anomalous data (1989). In that line of work, one of the key findings has been that a predisposition to a particular theory strongly influences the way in which subsequently presented data is seen or acknowledged. Attachment to an incorrect idea invites attention to only supportive data. Others have also made claims based in their readings this work and other relevant cognitive literature that incorrect preconceptions of scientific ideas will influence how students glean information from instructional representations in such a way that incorrect preconceptions will be supported (Kesidou & Roseman, 2002; Vosniadou, 1991). That is, if a learner already has an incorrect mental model or schema of a phenomenon in place, it would be very likely for that individual to see a diagram in such a way that would confirm their incorrect ideas. Incorrect ideas about science can be reinforced by diagrams.

These observations and considerations of the literature lend themselves to a set of hypotheses for how students' ideas about the seasons would be influenced by specific variants of orbit diagrams.

1. Elongations of the earth's orbit alone should be an appealing cue for the closer-farther explanation of the seasons because the diagram could be understood as depicting the elliptical shape of the Earth's orbit. Given a lone visual cue of an elongated orbit, more students should be drawn to a closer-farther explanation than in other diagram variants.
2. Multiple depth cues, such as the simultaneous use of elongation, shading, and object interpositionality, should work in concert to communicate to a student that the earth's orbit is depicted in perspective and discourage closer-farther explanations for the seasons. Perhaps one or more of those cues, such as shading, may inadvertently feed into a different conceptualization.
3. More students who already believe that the earth's elliptical orbit causes the seasons should, after having seen a drawing using an elliptical depiction,

maintain that conception than if given an alternative diagram that shows otherwise. The information that they glean from a diagram will be biased toward supporting their preconception.

4 Research method

4.1 Data source

A short written assessment was administered to 652 9th grade students by their regular science teachers. These students all belonged to the same school district in a metropolitan area in the Rocky Mountain region of the United States. For this particular school district, the cause of the seasons was to be included in the first multi-week instructional unit for the required ninth-grade Earth science class. Veteran science teachers in this district had confirmed for the researcher that the seasons was not understood by that grade level of students, and it had consequently been included as part of their district curriculum even though it was not specified according to their state or district standards.

In total, two junior high schools, five teachers, and 21 classes of Earth Science students in the district participated. When this study was conducted, no instructional unit had been begun. The first week of the school year in the two participating schools was dedicated solely to academic pre-tests and logistical issues related to classroom management, lab safety procedures, and school policies. Assessments were administered during week 1 or at the very beginning of week 2 prior to the beginning of any formal unit.

Each of the five teachers who distributed the assessment were explicitly trained in person by the researcher regarding how the assessments were to be administered, what language to use with respect to the assessment, and what student questions could or could not be answered by the teacher. The researcher-designed written assessment was a small packet that included two open-ended answer responses and a space for an optional drawing to be made by the student. The assessment was kept short at the request of the teachers and district administrators. The top of the question page asked students to think about why it was generally warmer in the summer and colder in the winter. Immediately following that, they were asked to complete two sentences:

1. "It is warmer in the summer because…"
2. "It is colder in the winter because…"

The following page stated simply that the students would look at a diagram similar to ones that appear in their textbooks and then be asked the same questions they had just answered. They were told that the individuals reading the students' next set of sentence completions would be different people than those who read the first set, so the students would need to be equally thorough in their written responses.

Following this, students needed to break an adhesive seal that prevented them from looking ahead in the packet. On the next page, students were shown one of six randomly assigned variants of an orbit diagram. These diagrams are shown in Figure 2 and are discussed further in the next section. Aside from some printed text ("Look at this picture that is based on one from a science textbook. You may refer back to this at any time.") the only thing on the page was a single orbit diagram. On the final page of the assessment, the two same open-ended response prompts and a space for drawing were presented again. The students were told that they could look back at earlier pages in their packet if they wished.

To summarize, this study involves the use of six randomly assigned treatment conditions. Students provided immediate pre- and post-diagram responses regarding their ideas about what caused seasonal temperature variation, and those were analyzed to infer diagrammatic influence on conceptualization.

4.2 Diagram design

A set of six diagrams was designed by the author for use in the study. These diagrams were intentionally based on a set of similar orbit diagrams that had appeared in the while the author was conducting a separate historical analysis of textbook illustrations (Lee, in press), and it was also based on orbit diagram exemplars presented by researchers in other media and research articles (e.g., Schnepps & Sadler, 1988).

In that set of diagrams that typically accompany explanations of the seasons, it is quite common for authors to include a depiction of four earths revolving around the sun (e.g., Watkins, Emiliani, Chiaverina, Harper, & LaHart, 1989). The correct proportions are not maintained, so the Earth and sun are both clearly visible and fit neatly on a quarter or half of a textbook page. All depictions that use perspective explicitly show the tilt of the earth's axis through the use of an axial line (or multiple axial lines when there is more than one Earth) extending from the North and South Pole. Sometimes, but not always, longitudinal and latitudinal lines are included. Outlines of countries on the Earth, usually North and South America, are typically shown. Some diagrams use shading, either as a gradient of darkness or as a discrete coloring pattern in such a way that the sun is understood as being located in the center and light is radiating out from it. Therefore, in depictions that use an oval shape, the top-most Earth is usually unshaded as the viewer's vantage point should show only the part of the Earth that is receiving and reflecting light.

Occasionally, some textbook drawings of the Earth's orbit have taken on a circular shape (e.g., Brandwein, Beck, Hollingworth, & Burgess, 1955). The idea here is that the viewer is positioned either above the North Pole, so most of what would be visible are the continents of the Northern Hemisphere. Prior research (Lee, 2008) has suggested that many students do not immediately recognize the continent shapes shown from this angle as being part of the Earth. Because of that, the current diagram designs, whether or not they used elliptical or circular shapes for orbital paths, did not incorporate depictions of continent shapes. Axis lines were not shown in the circle-shaped orbit depictions because, in committing to the idea that they were showing an approximation of a view from above the North pole, the axis would be reduced to a single point or a very short line segment contained in the earth shapes (Figure 2).

In the previous study (Lee, 2010), the diagrams that were used had many differences between them beyond the shape of the depicted orbit. There were differences in color, planet size, detail of the Earth's surface, and different amounts of additional information related to rotation, angle of tilt, and the role solar energy plays. What was common across all the previously examined diagrams, and with most other orbit diagrams that are used to explain the seasons, was the use of text to label the first days (equinoxes and solstices) of each of the four seasons. That use of text was intentionally preserved.

[INSERT Figure 2 AROUND HERE]

The full set of diagrams created for this study is shown in Figure 2. There were two parameters that were systematically varied: the eccentricity of the orbit, which would suggest different viewing angles, and the use of shading to indicate that the sun was emanating light. Increasing eccentricity progresses downward in Figure 2. The use of shading is shown in the two columns in that same figure. All six diagrams used equal-sized suns (with labels) and 4 equal-sized earth shapes (with labels indicating which earth was associated with the first day of each seasons). The horizontal span of each diagram was exactly the same. The vertical length of the diagram varied depending on the depicted orbit's eccentricity. Diagrams 3 and 6 both include interpositioned shapes, in which one earth should be seen as in front of the sun and another earth should be seen as being behind the sun. Diagrams 2, 3, 5, and 6 also include axis lines in order to be consistent with the implied viewing angle.

It is important to note, however, that the set of diagrams used in this study does not include any in which the sun is positioned anywhere but the center of the elliptical orbit shape. In such a diagram (such as the left drawing in Figure 1), one might place the sun at an elliptical focal point or toward one corner of the ellipse. These versions could be important to consider, as they may be especially amenable to the closer-farther misconception. They also bare resemblance to what some students will independently produce. However, the decision not to include these was based on the observation that most elliptical depictions in US textbooks position the sun in the center of the Earth's orbit (e.g., Mishra, 1999; Schnepps & Sadler, 1988). An informal, post-hoc examination and comparison with current science textbooks, confirmed that the diagrams used in this study were fair approximations, though less decorated versions, of what are still being used in many US science classrooms.

Also, if viewing angles were accurately shown in all aspects of the diagrams, the shaded and unshaded regions in the top and bottom Earths in Diagrams 2, 3, 5, and 6 would not be exactly circular. This would be because the viewing angle would allow for a small sliver of the Earth to be shaded or unshaded because of the position of the viewer. This is a detail that has not been included in any of the subsequently examined textbook diagram examples, and is also absent in the diagram examples shown in the literature (e.g., Mishra, 1999). In order to maintain consistency with what is typically given to students, that detail was not included in the present diagrams.

5 Analysis

A blind coder analyzed both pre- and post-diagram responses. This coder determined, whenever possible, what category of explanation that the student was giving. In 96.7% of the responses, this coder could associate the short answer responses and accompanying drawing with a single explanation. The other responses were considered unintelligible or a hybrid of multiple explanations for which none was dominant. These were designated as ‘other’, but kept in the analysis as the same students may have given a post-diagram response that could be coded. Multiple codings of the same set of responses were not allowed so as to enable quantitative analysis of independent observations.

5.1 Coding categories

In following with a set of distinctions described by Sherin (Sherin, under review; Sherin, Lee, & Krakowski, 2007), many students’ explanations for the causes of the seasons can be delineated into three major categories. These categorizations are central to this analysis. These include side-based, closer-farther, and tilt-based explanations.

1. *Side-based explanations.* In a side-based explanation, the rotational motion of the earth on its axis, rather than its orbit, is taken as central. One side of the earth is facing the sun while the other side is facing away from it. The absolute distance of the Earth from the sun is not different in this explanation. It would be more appropriately applied to describing the day and night cycle. The use of this class of explanation of the seasons has been observed elsewhere in the literature as well (e.g., Atwood & Atwood, 1996).

2. *Closer-farther explanations.* In closer-farther explanations, the cause of seasonal temperature variation is due to the distance of the Earth from the sun. Often, this involves the Earth's orbit and students who are asked to draw what they mean when giving a closer-farther explanation often produce a drawing that at least resembles something like Figure 1. Closer-farther explanations do not always have to include the orbit as part of them. Some students will simply state that the Earth is closer to the sun at one point during the year and far from it during another and make no mention of the earth as orbiting the sun. It is common across children and adults (Schnepps & Sadler, 1988; Trumper, 2006).

3. *Tilt-based explanations.* Tilt based explanations include both the scientifically accepted explanation, as well as explanations that otherwise invoke the Earth's axial

tilt. Other explanations include a description of how the tilt makes either the Northern or Southern hemisphere closer to the sun. This tilt can remain constant during the Earth's orbit, or it can be described as fluctuating.

While the three categories above will be the central focus of this analysis, two other categories are noted because they were distinct and identifiable across multiple iterative passes of the data. However, they did not comprise more than a small fraction of the total for any diagram condition. They are included to give the reader a sense as to the breadth of the data and responses that students provided. The final two categories include sunlight-based explanations and climate-based explanations.

4. Sunlight-based explanations. Sunlight-based explanations involve sunlight centrally, but do not consider the distance of the Earth, the tilt, or its orientation. Rather, solar energy is described as being directed or isolated to specific locations.
5. Climate-based explanations. Climate-based explanations involve description of the seasons as a result of changes in climate or weather. For example, descriptions of summer being hotter because the days being longer and hotter would fit into this category. Descriptions of winter being colder because of snow and ice also indicated a climate-based explanation. There were also notably a few students who attributed seasonal temperature variation to greenhouse gases or global warming.

Sample written responses from the corpus associated with these five categories are provided in Table 1.

[INSERT Table 1 AROUND HERE]

5.2 Reliability

Reliability was assessed by a three coders who were given a random subset of response data from about 15% of the student sample. Fleiss' kappa statistic (1973) was calculated to account for chance agreements. For kappa values, a coefficient of 0.6 or greater is considered to indicate strong reliability in categorical coding of data (Landis & Koch, 1977). The kappa coefficient determined by analysis of the codings assigned to the data subset was $\kappa=0.80$.

6 Patterns of initial responses across the six conditions

The initial response patterns for the students across the six diagram conditions were not significantly different from one another, as determined by a Chi-squared test ($\chi^2 = 15.94$, 25d.f., $p > 0.9$)[1]. The statistical result is taken as confirmation that initial assignment of students to diagram conditions was indeed random and the groups were comparable with one another. In general, there were ordinal similarities in the response distributions across each condition, prior to exposure to a diagram. Most students (nearly half in each group) gave tilt-based explanations. While that was the most common, it is important to note that almost all of the tilt-based explanations provided by students were scientifically

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[1] When only categories with more than 10 responses are considered only, or when Yates' correction to address small cell values is applied, the differences are still insignificant.

incomplete or incorrect. These explanations invoked hemispherical distance from the sun or generically involved tilt as something that makes one region of the Earth closer to the sun. The second most frequent response type was the closer-farther explanations and the third was side-based. The other codes applied to less than a tenth of each group.

[INSERT Table 2 AROUND HERE]

The fact that there were so many students who offered tilt-based explanations might seem initially surprising as that differs from what has been documented elsewhere in the literature that suggests the closer-farther explanation should be the most frequent (e.g., Atwood & Atwood, 1996; Newman & Morrison, 1993; Willard & Roseman, 2007). It is possible that the students had previously learned about axial tilt earlier in their schooling, although the official school-sanctioned classroom instruction around the seasons was scheduled to take place *after* this study. Some reasons why this sample had a higher number of tilt-based explanations could be due to any number of possible prior influences. In this particular school district, many students belong to a single dominant religious community in which international travel for missionary purposes is required for all males, and therefore the differences in climates across different regions of the Earth may be common knowledge passed along by family members and communities. Furthermore, many popular media sources, such educational television, are likely sources of knowledge that tilt the Earth's axis is tilted and somehow related to the seasons.

7 Results

7.1 Responses after diagram presentation

After viewing the diagram, the students were asked to write again responses to the same questions as before. Recall that in section 6, the distributions prior to examination of the assigned diagram were not significantly different from one another. The distribution of responses was quite different following examination of the diagram.

[INSERT Table 3 AROUND HERE]

From inspection of Table 3, it appears that many students had different explanations after viewing their assigned diagrams. For example, in diagrams 4 and 5, the side-based explanations are just as or more frequent than the tilt based explanations. The closer-farther explanation reduced in frequency across the board, appearing third most frequently now in all but diagram 2. Upon comparison with a Chi squared test ($\chi^2 = 45.25$, 25d.f., $p < 0.01$)[i], these distributions do not appear to be the same, as they were initially. This illustrates that the different diagrams did indeed have some effect.

7.2 Comparing the influences of different diagrams

In this section, I will compare the frequency of explanation types based on features shared by different diagrams. Specifically, I will revisit some of the predictions from section 3. In all of these analyses, exact binomial tests are used because the data were categorical in nature and involved dichotomous outcomes; either the responses belonged to the category of interest or they did not. When one set of frequencies is set as the reference point, significant differences can be determined by comparing the frequencies in a different condition compared and determining how likely the second set of frequencies could have been obtained if the groups were actually equivalent.

7.2.1 Do elliptical depictions cue students toward closer-farther explanations?

To determine the influence of elliptical depictions, two binomial tests were run first. The first compared the post-responses of the students who saw non-elliptical diagrams 1 or 4 against the responses of students who saw elliptical diagrams 2 or 5. Orbit shape was the dimension along which categories were established (i.e., the students were exposed to a circular or elliptical depiction). A two-sided binomial test run in the *R* statistics software package suggests that the likelihood for a closer-farther explanation is equal in both categories ($p > 0.7$). Similarly, when the elliptical category was replaced with the values determined by coding responses to diagrams 3 or 6, the results were also insignificant ($p > 0.6$).

Additional binomial tests were run comparing the post-diagram responses from students in different conditions who said the circle-shaped depiction against those who saw the elliptical-shaped ones. For example, only students who saw diagram 1 (circle-shaped) were compared against those who say diagram 2 (elliptical-shaped), and then only students who say diagram 1 (circle-shaped) were compared against those who saw diagram 3 (elliptical-shaped), etc. Again, there were no significant differences (at the 0.05 level) in any of these tests. From these results, it appears that there is no relationship between depicted circle and oval orbit shapes and the closer-farther explanation for the seasons. Contrary to what has been suggested and expected, that particular visual cue does not point students directly toward the predicted conceptualization.

7.2.2 Do more depth cues decrease the likelihood of closer-farther explanations?

From the previous set of results, it might seem unlikely that the presence of more cues decreased the likelihood of the closer-farther explanation, as that number did not significantly differ across the various explanations. To check whether or not that held true, post-diagram responses from diagrams 2 (which had an elliptical orbit shape only) and 6 (which had an elliptical orbit shape, overlapping shapes, and shading) were compared. This would offer the starkest contrast from the available data. A binomial test comparing the occurrence of the closer-farther explanation across the two diagram conditions does not show a significant difference between the two ($p > 0.5$).

7.2.3 Does the use of shading cue more side-based explanations?

Earlier work had shown side-based explanations to be more frequent in an interview setting (Lee, 2010). While here, tilt-based explanations were still the most frequent, the current study suggests that there was still a greater proportion of side-based explanations for students who examined the shaded diagrams 4, 5, 6 based on a median split. The common feature across those diagrams is the use of shading. A binomial comparison of all the unshaded diagram responses (1, 2, 3) against all the shaded ones (4, 5, 6) would suggest that shading does exert some influence ($p < 0.001$). This is confirmed by paired comparisons of diagram 2 and 5 responses ($p < 0.001$) and diagram 3 and 6 responses ($p < 0.01$). However, there is no significant difference in the frequency of side-based explanations in diagram 1 and diagram 4 responses ($p > 0.2$). Shading of half of the Earth appears to be a strong conceptualization cue towards side-based explanations when an elongated orbit shape accompanies it. It does not appear to privilege side-based explanations for circular orbit depictions. Presumably, this lack of influence in the circle-orbit conditions means that the shading does not add new information for those students who are prone to seeing a side-based explanation in their given diagram. Diagram 4 simply makes even more explicit what light and shading patterns are imagined by those who see diagram 1.

7.2.4 How is the frequency of tilt-based explanations being affected?

In this section, I consider how the frequency of the tilt-based explanation appears to be affected by the different diagram variants. Since diagrams 2, 3, 5, and 6 all have axial lines included, it would be safe to assume that those should all have more tilt-based explanations than responses given by students after having seen 1 or 4. To verify, the frequency of tilt-based explanations was tested against non-tilt-based explanations across individual diagrams. A binomial test comparing tilt-based explanations after seeing diagram 1 with those who saw diagram 2 indicated a significant difference ($p < 0.001$). Likewise, a significant difference also appears to be between diagram 1 and 3 ($p < 0.001$). Diagram 4 and 5 responses did not yield a significant increase in the number of tilt-based explanations ($p > 0.8$). However, tilt-based responses after examining diagram 6 did appear to be more frequent than those after examining diagram 4 ($p < 0.001$).

From those tests, there appeared to be an increase in tilt-based responses when unshaded elliptical diagrams with drawn tilts were used, regardless of whether the Earth and sun shapes were interpositioned on top of each other. When shading was added, a difference is only observed when interpositionality appears. This suggests that shading can be a more influential cue than an explicitly drawn axis or depicted orbit shape, and it initially draws students away from tilt-based explanations. This is evidenced by the increase in side-based responses from the diagram 5 group relative to the diagram 2 group.

However, adding an additional depth cue such as interpositionality counters some of shading's appeal. When there is overlap in the middle of the diagram, tilt regains primacy.

7.3 Discussion

From these analysis, it appears that the use of elliptical depictions in orbit diagrams do not sway students strongly toward the closer-farther explanation for the seasons that has been frequently identified in the literature. For perspective drawings, the use of shading is influential in general as a cue for side-based explanations, but that influence can be weakened by the interpositionality of shapes in a perspective drawing. When the influence of the shading cue is weakened, tilt-based explanations increase in relative frequency. When shading is not used on elliptical orbit depictions, or when it is used along with overlapping shapes, axial tilt forms the basis of an appealing explanation for many students.

The overall decrease in frequency of closer-farther explanations may come about for any number of reasons. For one, the distances between the two farthest points (which would correspond to opposite seasons) are equidistant from the sun. Any student who tries to impose the closer-farther explanation on the drawing would fail if they consider the sequential ordering of the seasons and are consistent in their application of any rules regarding distance and amount of heat received by an object. The use of text in the diagrams almost certainly influences their reasoning as well, as the ordering of the seasons is made explicit to any student who reads the labels. It might be possible that without any textual labels, students would be more inclined to give closer-farther explanations and disregard the equidistant positions of the opposing earths. However, while that may be borne out experimentally, it is nearly always the case that such labels are present in published orbit diagrams. Also, it has been observed that some students will disregard textual labels in the process of conceptualizing the seasons (Lee, 2008). Given those observations, an investigation of diagram influences that excludes such labels is not seen as pressing.

A curious result came about when both shading and interpositionality were simultaneously considered in section 7.2.4. When shading was present (diagram 5), there was a tendency for more students to give a side-based explanation. However, this was not the tendency for students who saw diagram 6, in which the Earth and sun overlap each other. This may be because, in the non-overlapping case, shading used to imply depth requires that the top and bottom Earth's be either wholly shaded or unshaded. That move to show depth using fewer cues (i.e., without interpositionality) may make a spatial interpretation of the Earth in a three-dimensional rotation around the sun initially more attractive, and therefore the side-based explanation is privileged. However, when the top and bottom Earth shapes that are interpositioned with each other or with the sun, the tilt may take precedence as the overlapping objects becomes processed generically as simply some region with a partially shaded conglomerate. This makes the tilt-based explanation appealing, as the side Earth's are easier to parse, and the tilt shown on them becomes more salient.

7.4 Reinforcement

The third prediction for how orbit diagrams would influence conceptualization, as listed in section 3, was that there would be more reinforcement of the closer-farther explanation due to the use of elliptical shapes to depict orbits. As the above results have shown, there was an overall decrease across all conditions in the use of closer-farther explanations. Those results suggest that, at the group level, the closer-farther explanation is not strengthened. It could be the case that a substantial number of students maintained the closer-farther explanation if they had started with it under specific diagram conditions. To examine that possibility, I present the numbers of students who moved away from their initial closer-farther explanation and those who maintained it across each of the diagram conditions.

[INSERT Table 4 AROUND HERE]

In comparing the relative proportions of students whose explanations changed to those that did not, in almost all diagram conditions a nearly 2:1 ratio appears (Table 4). There were far more students who moved away from the closer-farther explanation, even when presented with oval shaped orbits. Paired binomial tests revealed no significant differences between any two pairings of diagram-response groups. With these diagrams, we are not seeing any substantial, group-level reinforcement of the closer-farther explanation. However, it remains an open question as to whether or not some individuals who strongly subscribe to the closer-farther explanation find validation of that idea in the elliptical depictions. These data do not address that specific question, though some observational evidence elsewhere (e.g., Kikas, 1998) does suggest that could still be the case.

7.5 Explanation Migration

Considering that there were a large number of shifts away from an initial closer-farther explanation to after seeing a diagram, I would like to consider how all students' explanations shifted as a result of the different diagram. Might there be any pattern as to how a specific conceptualization changes in response to a set of visual cues?

To examine that issue, I produced a set of charts that map out how many students from a given explanation changed to another explanation (Figure 3). In these charts, the initial explanations are shown along the left column. The width of the rectangular shapes in that column is proportional to the number of students in that group who gave that answer. The rightmost column of rectangular shapes gives the same information, but for the number of students giving the associated explanation after being viewing their diagram. The arrows in between represent the number of students who moved from a group on the left to a group on the right. The thickness of the arrows is directly proportional to the numbers. When there were five or more students who shifted along a specific pathway, the arrow was given a black color. For any less than that, the arrow was given a gray color. The six different diagrams each have their own display.

There are a few observations to be made from this set of charts. First, there were not dramatic differences between the resulting explanations that came about after viewing diagram 1 and diagram 4 (two diagrams that differ only in the use of shading). Granted, some of the darker arrows are slightly thicker in one over the other, but the same migration pathways are preserved. This suggests that even though diagram 4 added shading, it did not change how students saw diagram 1 in a substantive way. We might even conclude from this that diagram 4 depicts what students already infer when viewing diagram 1, as suggested above in 7.2.3. A centrally located sun is interpreted as emanating energy in all directions, and only the half of a given earth shape nearest to the sun can receive that energy given the spatial configuration.

That similarity does not hold for the other shaded and unshaded pairs of diagrams (2 and 5, 4 and 6). In diagram 2, there were more students who migrated to a tilt-based explanation. For diagram 5, there were more students who migrated to the side-based explanation. It appears that when the two cues are shown together, the shading decreases the influence of the axial tilt line. It does not eliminate it entirely. There were many smaller arrows from other sources that still went to the tilt-based explanation.

In comparing the migration pattern of diagram 3 against that of diagram 6, the picture becomes less clear. There is more even distribution in terms of what explanations students migrate towards after seeing diagram 6. In panel 6, we can see five strong pathways compared to only two in panel 3. With 6, the case may be that there are enough individually attractive visual cues there that a student can latch onto a number of different explanations and comfortably settle there. Also, as described in section 7.2.4, the strong pull of the shading may be diminished by shape overlap. That weakening of the shading influence might make several other cues, beyond just tilt, attractive and therefore create more interpretive pathways for students.

One note to be made for all of the diagrams is that there are at least fifteen different pathways that are followed to six different categories of explanations. Despite some slight tendencies, as indicated by the darker lines, predicting where any given student will go based on presentation of a single diagram is still a non-trivial task.

[INSERT Figure 3 AROUND HERE]

8 Conclusion

This study was undertaken to consider the extent to which specific features in orbit diagrams act as conceptualization cues. Several analyses were performed to determine whether a set of predictions made under the assumption that conceptualization cues can strongly influence how students reason about the cause of the seasons. In consideration of the three hypotheses stated above, I offer the following conclusions

1) The closer-farther explanation is not privileged by elliptical depictions of the Earth's orbit. This could be due to reasons related to the typical use of labels (which are common in these diagrams), the inconsistencies that emerge conceptually when trying to reconcile equal distances for summer and winter, or the appeal of other potential explanations for the seasons.
2) Multiple cues communicating depth or perspective might help to dissuade students from offering the closer-farther explanation, but it does not seem to be any more influential than just one or two of the depth cues by themselves. Instead, the combination of depth cues may instead attract other explanations (such as the tilt-based one with diagram 6). The use shading does not appear to change how students view circle-shaped orbit diagrams that position the viewer above the North Pole.
3) At the group level, there does not appear to be a reinforcement effect of closer-farther explanations due to the use of elliptical orbit shapes in diagrams. Many students will readily change their explanation of the seasons in response to a presented diagram, but the exact trajectory of that change is not easy to pin down. At most, we can predict that a moderate number of students may follow certain

> pathways that are privileged by specific cue combinations. With rare exception, individual cues do not exert a strong enough pull by themselves to move students en masse to a single explanation.

The most general conclusion to be drawn from these analyses is that graphical cues can and might matter for individual diagrams, but they need not follow the seemingly most obvious trajectory. There are likely going to be a number of interdependencies between cues, in which one cue makes a certain way of thinking more likely, but then another counters it. While this challenges assertions previously made in the literature, it is still important that potential ways of understanding of diagrams are identified and posed by the research community as considerations for diagram design. However, any future claims made about how diagrams affect student thinking should still undergo empirical investigation, even when there seems to be an obvious cue and conceptualization connection to make.

9 Discussion

Diagrams have long been considered powerful for the knowing and teaching of science, but the influence that they have is not a direct one on students' ideas about the natural world. While past rhetoric has strongly suggested a pathway from cues to conceptions, it may be better to think of cues as elements interacting with other cues, and from those, a conceptualization emerges. Interactions between the cues and students' knowledge will not have a one-to-one relationship, and some of the explanations that emerge may bear little resemblance to what a focus on single diagram elements would suggest. In that regard, the interaction of student knowledge and diagrams may be more fruitfully thought of as a complex system, made up of prior knowledge and aspects of the presently available represented world. The emergent explanation need not look like the individual components that went into its formation.

Furthermore, there are some broader considerations one can make when considering what students' responses to diagrams tells us about intuitive and scientific understanding. Many students' ideas about the seasons were very sensitive to what could be thought of as only a minimal intervention. For those students who thought of the seasons as being the product of a closer-farther orbit around the sun, that idea was quickly abandoned or modified so much that they could be categorized by a coder as being a different explanation altogether. That rapid change suggests that students' prior conceptions, or even synthesized misconceptions, may lack contextual coherence (diSessa, Gillespie, & Esterly, 2004); that is, different mental models of phenomena will emerge depending on the changing specifics of a situation. While students may sometimes exhibit something like a stable meaning or idea, subtle changes to materials in the present situation can quickly demonstrate that that stability does not always hold. If that is true, the knowledge-in-pieces approach (diSessa, 1988) for studying student knowledge in science appears promising, and can be productively extended so that issues of knowledge and representation can be more deeply explored (e.g., Parnafes, 2007).

The recommendations that come out of this work are largely geared toward science education researchers. At a minimum, this study suggests we must be careful about the attributions we make to specific representational features. Even the most appealing connection, despite its prevalence and popularity in the field, requires some empirical data to verify that it is the right one to assert. We also should exercise caution with respect to what role we expect representations and inscriptions to play in student learning. While in principle, a trajectory of learning that moves students from one diagram to the next is possible, there is more to it than just the presentation of a carefully selected set of diagrams and inscriptions. Disciplined ways of seeing and making sense of representations must be considered as well.

With respect to instruction, the recommendations are more tentative because this was ultimately a minimal learning intervention. What we can glean from the results here is that diversity in interpretation and use of representations is quite common, even in the relatively simple case provided here. Across all six diagrams, a wide range of explanations emerged and shifted over a short period of time. At the very least, we can take from this the idea that representations rarely elicit uniform responses as instructional or learning tools. While there may be some slight tendencies, the conceptual outcomes are not deterministic. Teachers who wish to use representations as a 'common anchor' for instruction should attenuate their expectations with respect to how a diverse set of students will ultimately see and use a given diagram. Students will not come to the same understanding because of one carefully selected or designed representation. This poses a challenge for how teachers should optimally use representations in their teaching. One suggestion would be for teachers to provide clear scaffolding with respect to the key features should notice in a diagram. Simple acts such as pointing and gesturing around representations can do a great deal to direct attention and support reading of visual information (Valenzeno, Alibali, & Klatzky, 2003). Teachers can also model by thinking out-loud how he or she makes sense of a diagram and then reconciles it with her own conceptual knowledge. This could help students to know what visual cues to consider as more central in a diagram, and what importance to place on those and their intuitive understandings of the science topic at hand. Also, inviting students to make public how they see and understand diagrams, through more open classroom discussions, could be productive. It would allow for classes of students to establish norms for reading specific classes of diagrams. Such an approach is appearing more in teaching interventions that focus on engaging students in modeling practices. There, cycles of critique and sense-making around drawn representations take place, and students establish criteria or elements that should or should not be taken as meaningful (diSessa, Hammer, Sherin, & Kolpakowski, 1991; Schwarz, et al., 2009). In general, these recommendations all are different approaches one might take to reposition visual representations, like diagrams, as objects for students to contemplate and comment upon. That positioning would be an alternative to what happens as part of standard teaching practices, in which diagrams serve more as 'given objects' around which intuitive knowledge must somehow immediately conform.

9.1 Study limitations

While this work was an attempt to transcend limitations of an earlier study, this study is still limited in several regards. First, none of the diagrams that were used do much to facilitate a correct understanding of the cause of the seasons, largely because they do not make explicit how solar energy and the incident angle of light is involved. It would be possible to make some claims from this work about which diagram format is most effective relative to other variants of the same theme, but it would not be appropriate to conclude from this work that one of these diagrams is truly ideal for use in teaching the seasons.

However, these kinds of diagrams are the ones most often presented to students in existing commercial curriculum materials, and should merit at least some careful consideration for that reason alone.

While I made some tentative instructional recommendations, I offer no conclusions regarding how students will ultimately perform in a structured learning experience that uses such diagrams. There are many different formats that instruction could take. For example, these diagrams could be critiqued as part of a model-building learning experience in which the diagrams are objects for them to modify rather than simply read. Or they might be embedded in expository text or a lecture in which other information that is introduced has additional effects and changes what cues are salient and what interactions take place. If the latter case, a framework that considers how text and diagrams interact would be more appropriate to consider (Schnotz, 2002). Ultimately, what this study does is isolate some variables, but it does not tell us what will happen when the representation is embedded in the complexities of the science curriculum or classroom.

Finally, this sample may have seemed unusual in two regards. First, it exhibited regularity in the initial presentation on the tilt-based explanation. This is rather curious considering the prominence of the closer-farther explanation elsewhere in the literature. As this study was done at the beginning of the academic year, we cannot attribute any immediate prior instruction to this result. We can speculate that this patterning may be the product of at least a decade of time during which these students had been informally exposed to the idea of a tilted earth or seasonal differences in different hemispheres. It may be that somehow the specific probes and instrument might have somehow privileged that response. Second, some skeptics might still be uncertain if these results could be replicated, as what had been predicted as the likely misreading of the orbit diagrams by so many others did not happen with these students. It may be that with respect to reading diagrams, the students in this age group were mature enough to avoid making the predicted mistakes. As diSessa & Sherin (2000) have observed, by the time science students are examined in a formal education research study, they have years of experience working with representations. The students in this sample surely had developed some degree of intuitive competence for using and working with representations like the ones they were shown here. If that is what leads to the present results, an intriguing replication of this study could test when that competence manifests itself in a specific content area. Perhaps a more developmental approach could be taken that tracks when and how that competence develops over time. Both would be fruitful directions for future research.

10 References

Achér, A., Arca, M., & Sanmarti, N. (2007). Modeling as a Teaching Learning Process for Understanding Materials: A Case Study in Primary Education. *Science Education, 91*(3), 398-418.

American Association for the Advancement of Science (2002). Middle Grade Science Textbooks: A benchmarks-based evaluation. Retrieved August 6, 2006, from http://www.project2061.org/publications/textbook/mgsci/report/index.htm.

Atwood, R. K., & Atwood, V. A. (1996). Preservice elementary teachers' conceptions of the causes of seasons. *Journal of Research in Science Teaching, 33*(5), 553-563.

Barab, S. A., Hay, K. E., Barnett, M., & Keating, T. (2000). Virtual solar system project: Building understanding through model building. *Journal of Research in Science Teaching, 37*(7), 323-357.

Brandwein, P. F., Beck, A. D., Hollingworth, L. G., & Burgess, A. E. (1955). *You and Science: Science for Better Living*. New york: Harcourt Brace.

Carr, T. H., McCauley, C., Sperber, R. D., & Parmelee, C. M. (1982). Words, pictures, and priming: On sematic activation, conscious identification, and the automaticity of information processing. *Journal of experimental psychology: Human perception and performance, 8*(6), 757-777.

Carvalho, G. S., Silva, R., & Clement, P. (2007). Historical analysis of Portuguese primary school textbooks (1920-2005) on the topic of Digestion. *International Journal of Science Education, 29*(2), 173-193.

Cavanagh, P., & Leclerc, Y. G. (1989). Shape from shadows. *Journal of experimental psychology: Human perception and performance, 15*(1), 3-27.

Cho, H.-H., Kahle, J. B., & Nordland, F. H. (1985). An investigation of high school biology textbooks as sources of misconceptions and difficulties in teaching genetics and some suggestions for teaching genetics. *Science Education, 69*(5), 717-719.

Colin, P., Chauvet, F., & Viennot, L. (2002). Reading images in optics: students' difficulties and teachers' views. *International Journal of Science Education, 24*(3), 313-332.

Cook, M. P. (2006). Visual representations in science education: The influence of prior knowledge and cognitive load theory on instructional design principles. *Science Education, 90*, 1073-1091.

Cook, M. P., Wiebe, E. N., & Carter, G. (2008). The influence of prior knowledge on viewing and interpreting graphics with macroscopic and moleculear represnetations. *Science Education, 92*, 848-867.

Cutting, J. E., & Vishton, P. M. (1995). Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth. In W. Epstein & S. Rogers (Eds.), *Handbook of perception and cognition, Vol 5: Perception of space and motion* (Vol. 5, pp. 69-117). San Diego, CA: Academic Pres.

diSessa, A. A. (1988). Knowledge in pieces. In G. Forman & P. Pufall (Eds.), *Constructivism in the computer age.* Hillsdale, N. J.: Lawrence Erlbaum.

diSessa, A. A., Gillespie, N. M., & Esterly, J. B. (2004). Coherence versus fragmentation in the development of the concept of force. *Cognitive Science, 28*, 843-900.

diSessa, A. A., Hammer, D., Sherin, B., & Kolpakowski, T. (1991). Inventing graphing: Meta-representational expertise in children. *Journal of Mathematical Behavior, 10*, 117-160.

diSessa, A. A., & Sherin, B. L. (2000). Meta-representation: An introduction. *Journal of Mathematical Behavior, 19*(385-398).

Duschl, R. A., Schweingruber, H. A., & Shouse, A. W. (2007). *Taking science to school: Learning and teaching science in grades K-8*. Washington, DC: The National Academies Press.

Fleiss, J. L. (1973). *Statistical methods for rates and proportions*. New York: John Wiley & Sons.

Glasgow, J., Narayanan, N. H., & Chandrasekaran, B. (1995). *Diagrammatic Reasoning: Cognitive and Computational Perspectives*. Menlo Park, CA: AAAI Press.

Han, J., & Roth, W. M. (2006). Chemical inscriptions in Korean textbooks: Semiotics of macro- and microworld. *Science Education, 90*, 173-201.

Hegarty, M., Carpenter, P. A., & Just, M. A. (1990). Diagrams in the comprehension of scientific texts. In R. Barr, M. L. Kamil, P. Mosenthal & P. D. Pearson (Eds.), *Handbook of reading research* (pp. 641-668). New York: Longman.

Heiser, J., & Tversky, B. (2006). Arrows in comprehending and producing mechanical diagrams. *Cognitive Science, 30*, 581-592.

Hochberg, C. B., & Hochberg, J. (2007). Familiar size and the Perception of Depth. In M. A. Peterson, B. Gillam & H. A. Sedgwick (Eds.), *In the mind's eye* (pp. 3-10). New York: Oxford University Press.

Hsu, Y.-S. (2008). Learning about seasons in a technologically enhanced environment: The impact of teacher-guided and student-centered instructional approaches on the process of students' conceptual change. *Science Education, 92*(2), 320-344.

Kesidou, S., & Roseman, J. E. (2002). How well do middle school science programs measure up? Findings from Project 2061's curriculum review. *Journal of Research in Science Teaching, 39*(6), 522-549.

Kikas, E. (1998). Pupils' explanations of seasonal changes: age differences and the influence of teaching. *British Journal of Educational Psychology, 68*, 505-516.

Kuhn, D. (1989). Children and adults as intuitive scientists. *Psychological Review, 96*(4), 674-689.

Kunnapas, T. (1968). Distance perception as a function of available visual cues. *Journal of Experimental Psychology, 77*(4), 523-529.

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics, 33*(1), 159-174.

Larkin, J. H., & Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive science, 11*, 65-99.

Latour, B. (1987). *Science in action : how to follow scientists and engineers through society*. Cambridge, Mass.: Harvard University Press.

Lee, V. R. (2008). *Getting the picture: A mixed-methods inquiry into how visual representations are interpreted by students, incorporated within textbooks, and integrated into middle-school science classrooms.* Unpublished Doctoral Dissertation, Northwestern University, Evanston, IL

Lee, V. R. (2010). *Misconstruals or more? The interactions of orbit diagrams and explanations of the seasons.* Paper presented at the 2010 Annual Meeting of the American Educational Research Association.

Lee, V. R. (in press). Adaptations and continuities in the use and deisgn of visual representations in US middle school science textbooks. *International Journal of Science Education*.

Macdonald-Ross, M. (1979). Scientific digrams and the generation of plausible hypotheses: An essay in the history of ideas. *Instructional Science, 8*, 223-234.

Mayer, R. E. (1997). Multimedia learning: Are we asking the right questions? *Educational Psychologist, 32*(1), 1-19.

Mayer, R. E. (2001). *Multimedia learning*. Cambridge ; New York: Cambridge University Press.

Medin, D. L., Ross, B. H., & Markman, A. B. (2001). *Cognitive Psychology (Third Edition)*. Orlando, FL: Harcourt.

Meir, E., Perry, J., Herron, J. C., & Kingsolver, J. (2007). College students' misconceptions about evolutionary trees. *The American Biology Teacher, 69*(7), 71-76.

Mishra, P. (1999). The role of abstraction in scientific illustration: Implications for Pedagogy. *Journal of Visual Literacy, 19*(2), 139-158.

Newman, D., & Morrison, D. (1993). The conflict between teaching and scientific sense-making: The case of a curriculum on seasonal change. *Interactive Learning Environments, 3*, 1-16.

Parnafes, O. (2007). What Does “Fast” Mean? Understanding the Physical World Through Computational Representations. *Journal of the learning sciences, 16*(3), 415-450.

Roth, W. M. (2008). The nature of scientific conceptions: A discursive psychological perspective. *Educational Research Review, 3*, 30-50.

Roth, W. M., & Middleton, D. (2006). Knowing what you tell, telling what you know: Uncertaint and asymmetries of meaning in interpreting graphical data. *Cultural Studies of Science Education, 1*, 11-81.

Roth, W. M., Pozzer-Ardenghi, L., & Han, J. (2005). *Critical Graphicacy: Understanding visual representation practices in school science*: Springer.

Sadler, P. M. (1987). *Alternative conceptions in astronomy*. Paper presented at the Second international seminar on Misconception and Educational Strategies in Science and Mathematics.

Salierno, C., Edelson, D., & Sherin, B. (2005). The Development of Student Conceptions of the Earth-Sun Relationship in an Inquiry-Based Curriculum. *Journal of Geoscience Education, 53*(4), 422-431.

Schnepps, P., & Sadler, P. (1988). A private universe: An insightful lesson on how we learn. Santa Monica, CA: Pyramid Film & Video.

Schnotz, W. (2002). Toward an integrated view of learning from text and visual displays. *Educational Psychology Review, 14*(1), 101-120.

Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Achér, A., Fortus, D., et al. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners *Journal of Research in Science Teaching, 46*(6), 632-654.

Sherin, B. (under review). Computational studies of commonsense science: An exploration in the automated analysis of clinical interview data.

Sherin, B., Lee, V. R., & Krakowski, M. (2007). Conceptual dynamics in clinical interviews *Physics Education Research Conference (PERC)* (pp. 23-36). Greensboro, NC.

Stenning, K., & Oberlander, J. (1995). A cognitive theory of graphical and linguistic reasoning: Logic and implementation. *Cognitive Science, 19*(1), 97-140.

Stern, L., & Roseman, J. E. (2004). Can middle-school science textbooks help students learn important ideas? Findings from Project 2061's curriculum evaluation study: Life science. *Journal of Research in Science Teaching, 41*(6), 538-568.

Treagust, D., Chittleborough, G., & Mamiala, T. (2002). Students' understanding of the role of scientific models in learning science. *International Journal of Science Education, 24*(4), 357-368.

Trumper, R. (2006). Teaching future teachers basic astronomy concepts-- seasonal changes-- at a time of reform in science education. *Journal of Research in Science Teaching, 43*(9), 879-906.

Tufte, E. R. (1983). *The visual display of quantitative information*. Cheshire, Conn.: Graphics Press.

Valenzeno, L., Alibali, M. W., & Klatzky, R. (2003). Teachers' gestures facilitate students' learning: A lesson in symmetry. *Contemporary Educational Psychology, 28*(2), 187-204.

Vosniadou, S. (1991). Designing curricula for conceptual restructuring: Lessons from the study of knowledge acquisition in astronomy. *Journal of Curriculum Studies, 23*(3), 219-237.

Wampler, J. M. (2002). Misconceptions - A column about errors in geoscience textbooks: Misconception of energy release in earthquakes. *Journal of Geoscience Education, 50*(5), 620-623.

Watkins, P. A., Emiliani, C., Chiaverina, C. J., Harper, C. T., & LaHart, D. E. (1989). *General Science*. Orlando, FL: Harcourt, Brace, & Jovanovich.

Willard, T., & Roseman, J. E. (2007). *Progression of Understanding of the Reasons for Seasons*. Paper presented at the Knowledge Sharing Institute of the Center for Curriculum Materials in Science.

Yu, K. C., & Sahami, K. (2008). Visuospatial astronomy education in immersive digital planeteriums. In M. Zoulias & I. Robson (Eds.), *Communicating Astronomy with the Public*. Athens, Greece: Eugenides.

Table 1

Sample student responses.

Explanation Category	Sample Response
Closer-farther explanations	"It is warmer in the summer because that's when our side of the Earth is closer to the sun than the other side. It is colder in the winter because our side of the Earth is facing away from the sun and towards the moon." *(Student 34)*
Side-based explanations	"It is warmer in the summer because when our Earth orbits the sun, the sun isn't in the middle of the Earth's orbit, so when its closer it's in the summer. It is colder in the winter because the Earth is farther away from the sun, and so there isn't as much warmth and light." *(Student 636)*
Tilt-based explanations	"It is warmer in the summer because the Earth is tilted on an axis, so we are getting more direct rays from the sun. It is colder in the winter because the Earth is tilted differently from above, so the rays hit us at a different and less direct angle." *(Student 478)*
Sunlight-based explanations	"It is warmer in the summer because the sun is hitting that part of the Earth the most. It is colder in the winter because the sun is barely hitting that part of the earth." *(Student 124)*
Climate-based explanations	"It is warmer in the summer because the sun is out more. It is colder in the winter because it usually snows." *(Student 401)*

Table 2

Counts of student explanations of the seasons prior to presentation of diagrams

	Side-based	Closer-Farther	Tilt-Based	Sunlight-based	Climate-based	Other	Total
Diagram 1	21 (19.6%)	23 (21.5%)	43 (40.2%)	11 (10.3%)	6 (5.6%)	3 (2.9%)	107
Diagram 2	16 (13.7%)	28 (23.9%)	59 (50.4%)	5 (4.3%)	7 (4.2%)	2 (1.7%)	117
Diagram 3	13 (13.3%)	27 (27.6%)	45 (45.9%)	4 (4.1%)	8 (8.1%)	1 (1.0%)	98
Diagram 4	15 (13.9%)	28 (25.9%)	48 (44.4%)	9 (8.3%)	6 (5.6%)	2 (1.9%)	108
Diagram 5	17 (15.0%)	26 (23.0%)	48 (42.5%)	8 (7.1%)	9 (8.0%)	5 (4.4%)	113
Diagram 6	19 (17.4%)	20 (18.3%)	51 (46.8%)	7 (6.4%)	10 (9.2%)	2 (1.8%)	109
Total	101	152	294	44	46	15	652

Table 3

Counts of student explanations of the seasons after presentation of the diagrams

	Side-based	Closer-Farther	Tilt-Based	Sunlight-based	Climate-based	Other	Total
Diagram 1	28 (26.2%)	15 (14.0%)	46 (43.0%)	8 (7.5%)	6 (5.6%)	4 (3.7%)	107
Diagram 2	21 (17.9%)	16 (13.7%)	69 (59.0%)	3 (2.6%)	1 (0.9%)	7 (6.0%)	117
Diagram 3	15 (15.3%)	16 (16.3%)	53 (54.1%)	6 (86.1%)	2 (2.0%)	6 (6.1%)	98
Diagram 4	34 (31.5%)	21 (19.4%)	38 (35.2%)	9 (8.3%)	2 (1.9%)	4 (3.7%)	108
Diagram 5	44 (38.9%)	16 (14.2%)	39 (34.5%)	7 (6.2%)	1 (0.9%)	6 (5.3%)	113
Diagram 6	29 (26.6%)	17 (15.6%)	53 (48.7%)	6 (5.5%)	2 (1.8%)	2 (1.8%)	109
Total	171	101	298	39	14	29	652

Table 4

Numbers and percentages of students who changed or maintained the closer-farther explanation

	Changed away from Closer-Farther explanation	**Maintained Closer-Farther Explanation**
Diagram 1	16 (69.6%)	7 (30.4%)
Diagram 2	17 (60.7%)	11 (39.3%)
Diagram 3	19 (70.4%)	8 (29.6%)
Diagram 4	19 (67.9%)	9 (32.1%)
Diagram 5	18 (69.2%)	8 (30.8%)
Diagram 6	13 (65.0%)	7 (35.0%)

Figure 1

Student drawings used to explain their ideas about why there are different temperatures during different seasons.

Figure 2

Orbit diagrams presented to students.

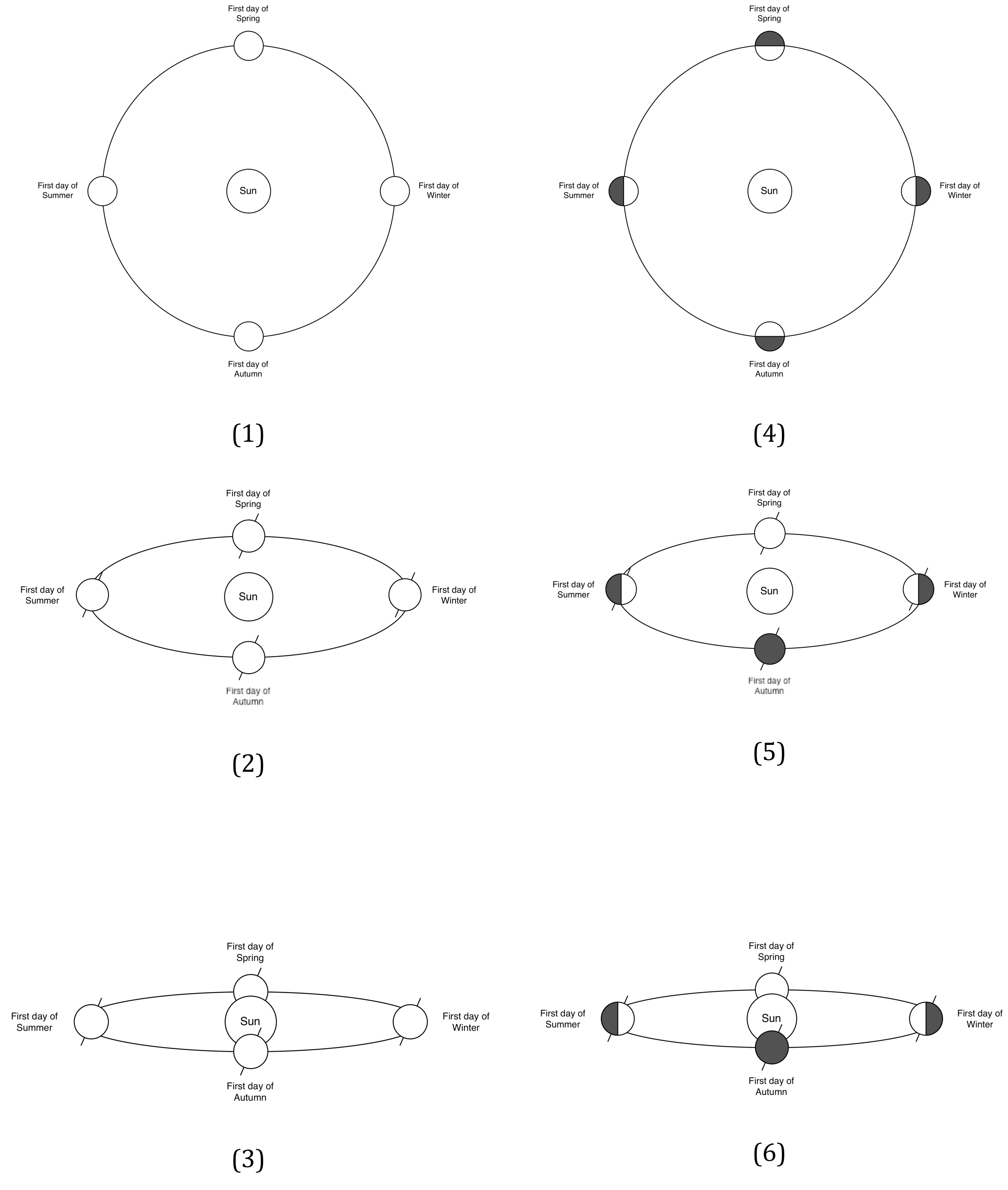
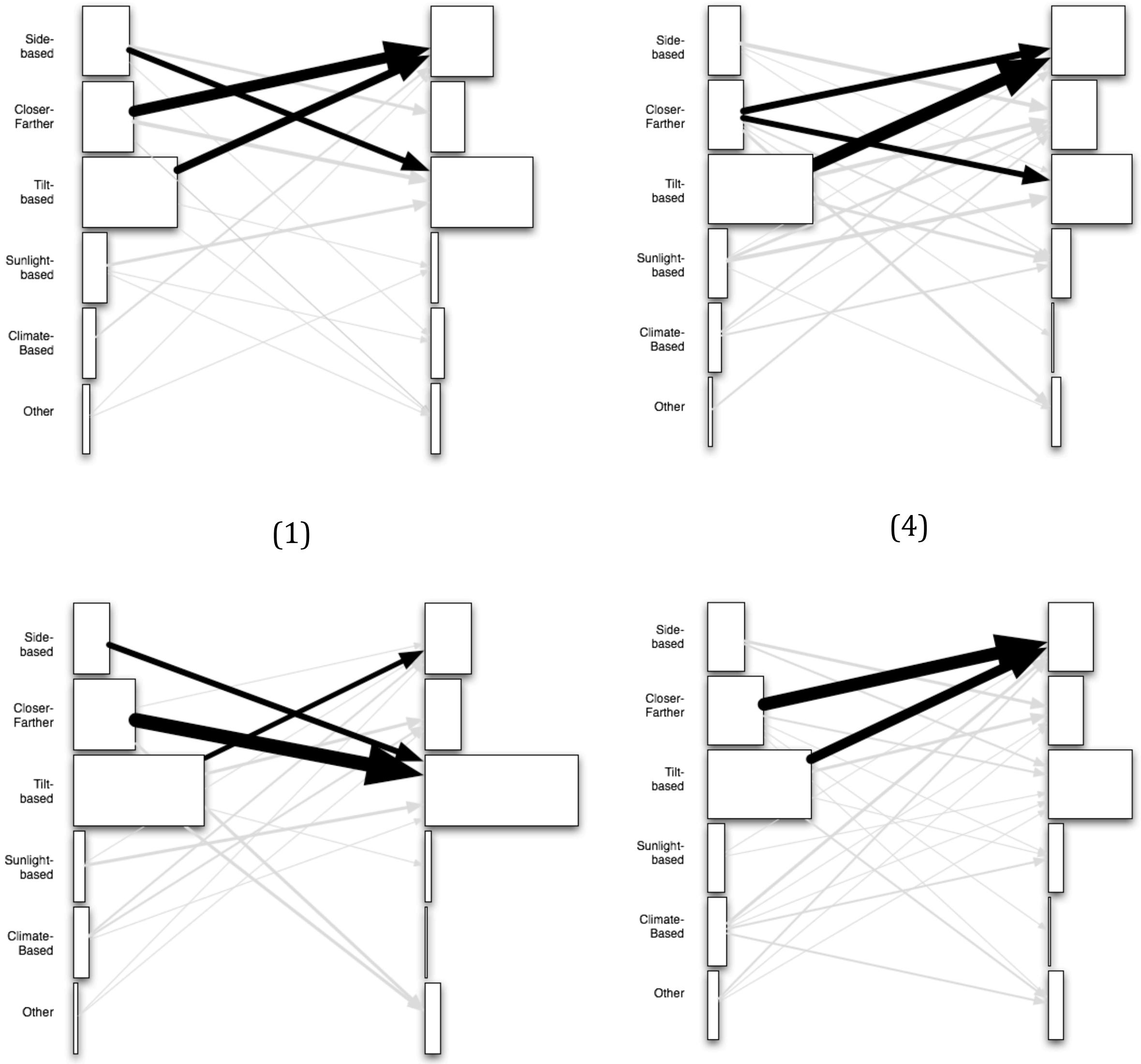


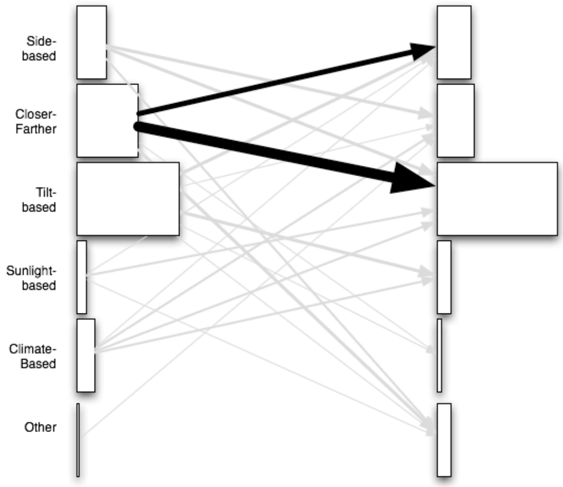
Figure 3

Migration patterns before and after examination of diagrams

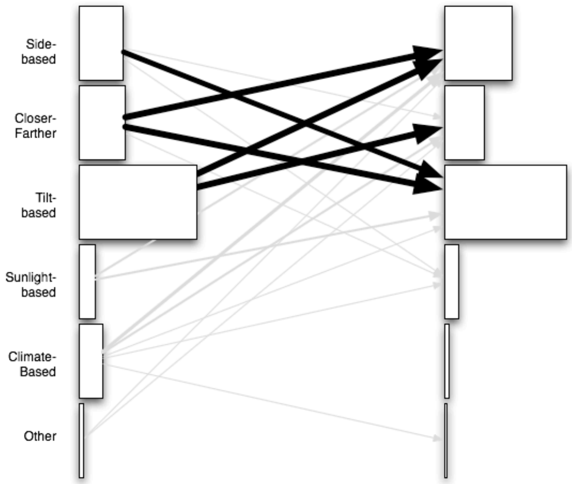


(1) (4)

(2) (5)


Side-
based
Closer-
Farther
Tilt-
based
Sunlight-
based
Climate-
Based
Other

(3)


Side-
based
Closer-
Farther
Tilt-
based
Sunlight-
based
Climate-
Based
Other

(6)

11 Footnotes

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[i] $\chi^2 = 37.77$, 25 d.f., $p < 0.05$ if Yates' correction for small cell values is applied. This result is still significant.